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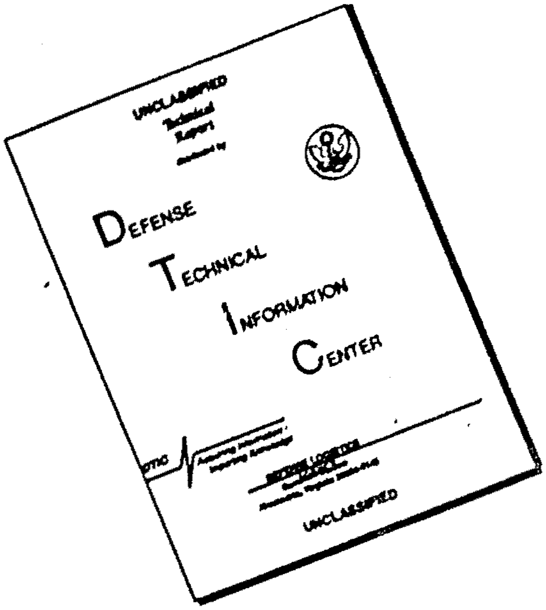

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AIR FORCE MISSILE DEVELOPMENT CENTER

TECHNICAL REPORT

WEAR, SOLID LUBRICATION, AND BEARING MATERIAL INVESTIGATION FOR HIGH-SPEED TRACK APPLICATIONS

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NOX

LLOMAN AIR FORCE BASE
NEW MEXICO

March 1960

Contract AF 29(600)-1516

WEAR, SOLID LUBRICATION, AND BEARING MATERIAL INVESTIGATION FOR HIGH-SPEED TRACK APPLICATIONS

by

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AIR FORCE MISSILE DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
Holloman Air Force Base, New Mexico

March 1960

FOREWORD

Test-track slipper friction, wear, and lubrication have been under consideration for the past ten years or more by track designers and operators. A segment of this activity was a joint effort by the Air Force Missile Development Center and Stanford Research Institute (SRI).

AFMDC awarded Contract AF 29(600)-1516 to SRI to investigate slipper bearing materials and lubricating track coatings for the period February 1958 to June 1959.

This report covers the above investigation and is complementary to the contractor's final report. It is written strictly from a track operator's viewpoint.

ACKNOWLEDGMENTS

The author is indebted to the Physics Department of Stanford Research Institute and the Track Test Division for making it possible to complete the experimental program despite a rigorous time schedule. It is noteworthy that the Track Operations Branch conducted four firings a day on six occasions and once on two successive days.

ABSTRACT

High-speed wear and lubrication were investigated on 60 track tests, made with the Stanford Research Institute test slipper. The variables were velocity, bearing material, nominal bearing pressure, and track condition.

Wear rate of stainless steel increased with velocity (825 to 2,500 fps) while there was little or no apparent effect on molybdenum. Wear rate was reduced by several solid track coatings, most notably by metallic zinc and slaked lime.

PUBLICATION REVIEW

This Technical Report has been reviewed and is hereby approved for publication.

FOR THE COMMANDER:

KNOX MILLSAPS
Chief Scientist

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WEAR, SOLID LUBRICATION, AND BEARING MATERIAL INVESTIGATION FOR HIGH-SPEED TRACK APPLICATIONS

I. INTRODUCTION

The problem of friction and wear under high-speed sliding conditions is not a new one, nor is it unique to the Holloman track or tracks in general. However, this presentation is limited to investigations directly concerned with track problems, namely increasing the wear resistance and load carrying capacity of slippers.

These efforts are aimed at extending track testing capability and reliability. Track operators are confronted with requirements for attaining higher velocities and acceleration with larger vehicles. The vehicles are designed to fulfill the needs of track users, and quite often aerodynamic and structural loads are of secondary consideration. Excessive slipper reactions lead to slipper failure, either through catastrophic wear or structural inadequacy. Minimizing wear also contributes to decreasing the vehicular vibrational environment. It is accepted that the closer the slipper fits the railhead, the smoother the ride, and a tight-fitting slipper at the breech becomes progressively looser as it wears.

Attempts to increase slipper capabilities are almost as numerous as individual investigators, but this discussion is limited to the two major advances in decreasing slipper wear.

1. Historical Background

The first break-through is history, and started over three years ago at the U. S. Naval Ordnance Test Station (NOTS). Thirty-one track tests were made with mechanically loaded test samples. These tests were controlled as closely as possible, and only the material and pressures were purposely varied during the program.

The data from this unsophisticated test program are plotted in a family of wear versus pressure curves (Fig. 1), and are surprisingly consistent with later work. At this point let it suffice to note that stainless steel and stellite wore about the same, and plain carbon 1020 steel wore the least. Unfortunately, the 1020 results were of questionable accuracy because the tests were run the day after it rained, and the track was covered with a fresh, powdery rust layer. This program and others had already proved the efficiency of the lower oxides of iron as a lubricant (Ref. 1).

Released by author March 1960.

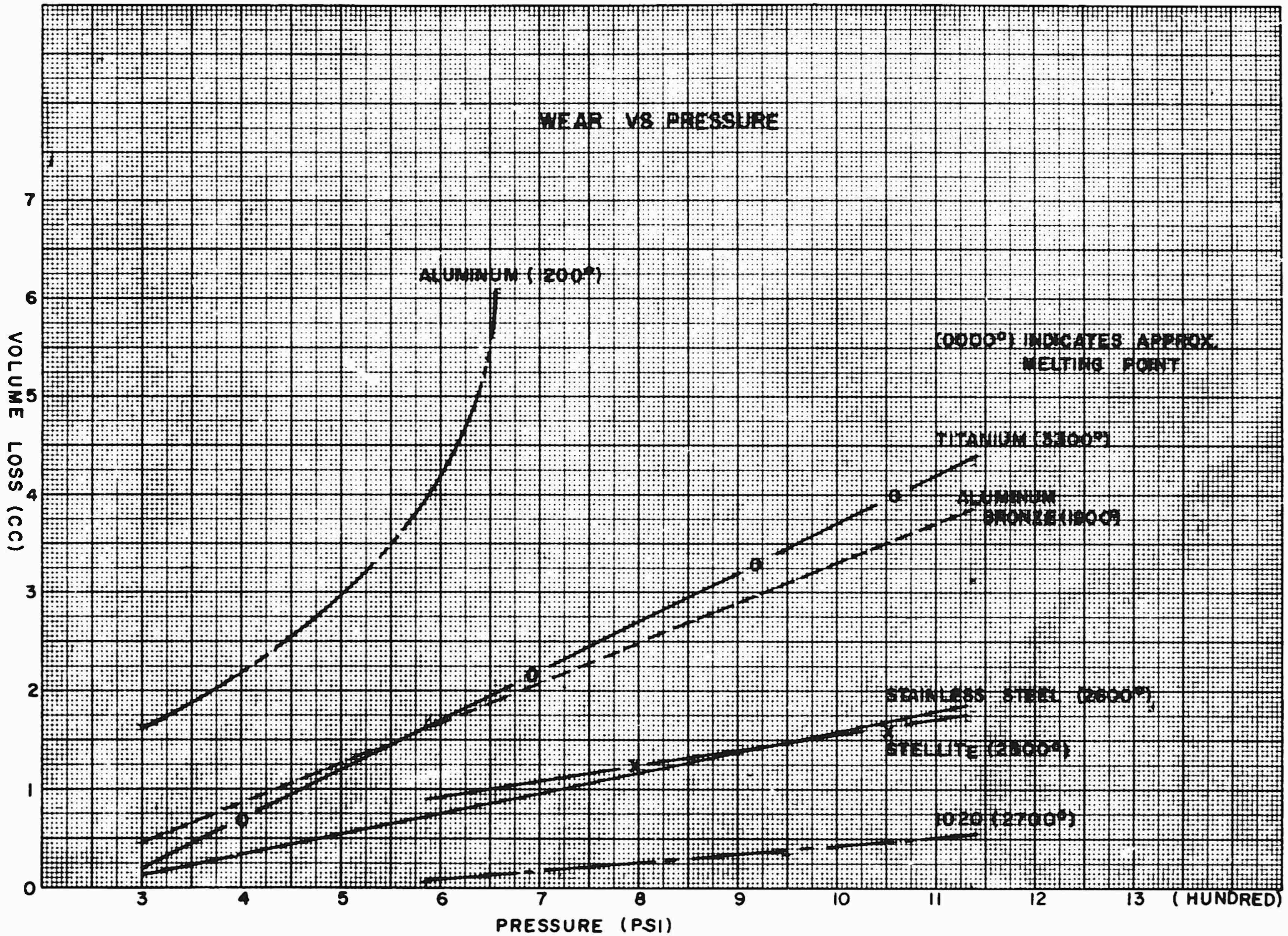

FIGURE 1. Wear Versus Pressure

While the engineering material investigation was underway, a research contract was let to Stanford Research Institute (SRI) to investigate the mechanisms of high-speed sliding friction and wear (in other words, an investigation of the processes involved in the loss of bearing material). This research was based on the obvious assumption that an understanding of the mechanisms of wear would lead to the development of methods of minimizing it.

A comparatively sophisticated track test program of 23 runs was completed with an SRI test slipper. The original model of this current slipper (Fig. 2 and 3) was the primary experimental tool. The present models, like the original, are capable of pneumatically loading a two-square-inch test sample with bearing pressures up to 1500 psi once each run and unloading the test sample once each run, both at predetermined locations.

At the conclusion of the test program (Ref. 2) it was postulated that:

a. The wear rate is time-dependent, increasing progressively from a low initial value toward a steady-state value as time increases.

b. Melting of the bearing material is the primary mechanism of wear. As a result of this postulate, which indicates wear resistance is a function of (among other things) melting point and thermal conductivity, molybdenum, with a melting point of about 4700°F, was tested, and wore one-tenth as much as stainless steel under similar conditions. Consequently, the wear resistance of standard inserts was improved by an order of magnitude and is the first major accomplishment previously mentioned in the introduction.

Referring back to the wear versus pressure curves (Fig. 1) demonstrates that at low nominal pressures there are many standard engineering alloys which show little wear. But as the nominal pressure increases, major differences in wear resistance appear. Consequently it can be concluded that excessive wear becomes a problem at high bearing pressures.

The curves are also in agreement with the wear theory. Wear resistance varies with the melting point except for the titanium series, which can be explained by its affinity to both oxygen and nitrogen at elevated temperatures. It burns vigorously in nitrogen at 1475°F.

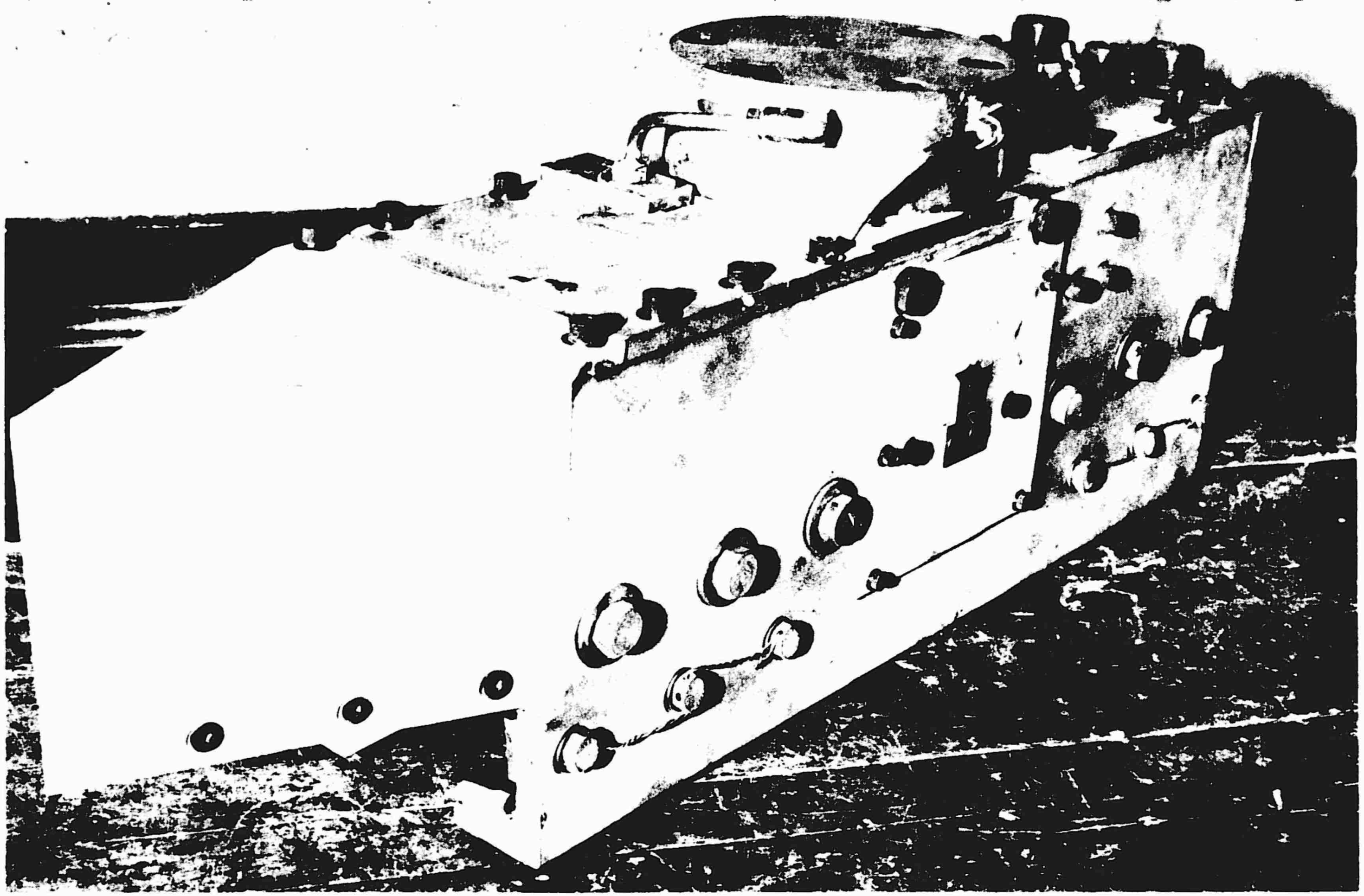

FIGURE 2. SRI Test Slipper After First Three Runs (24-25 April 1958)
Three-quarter Front View

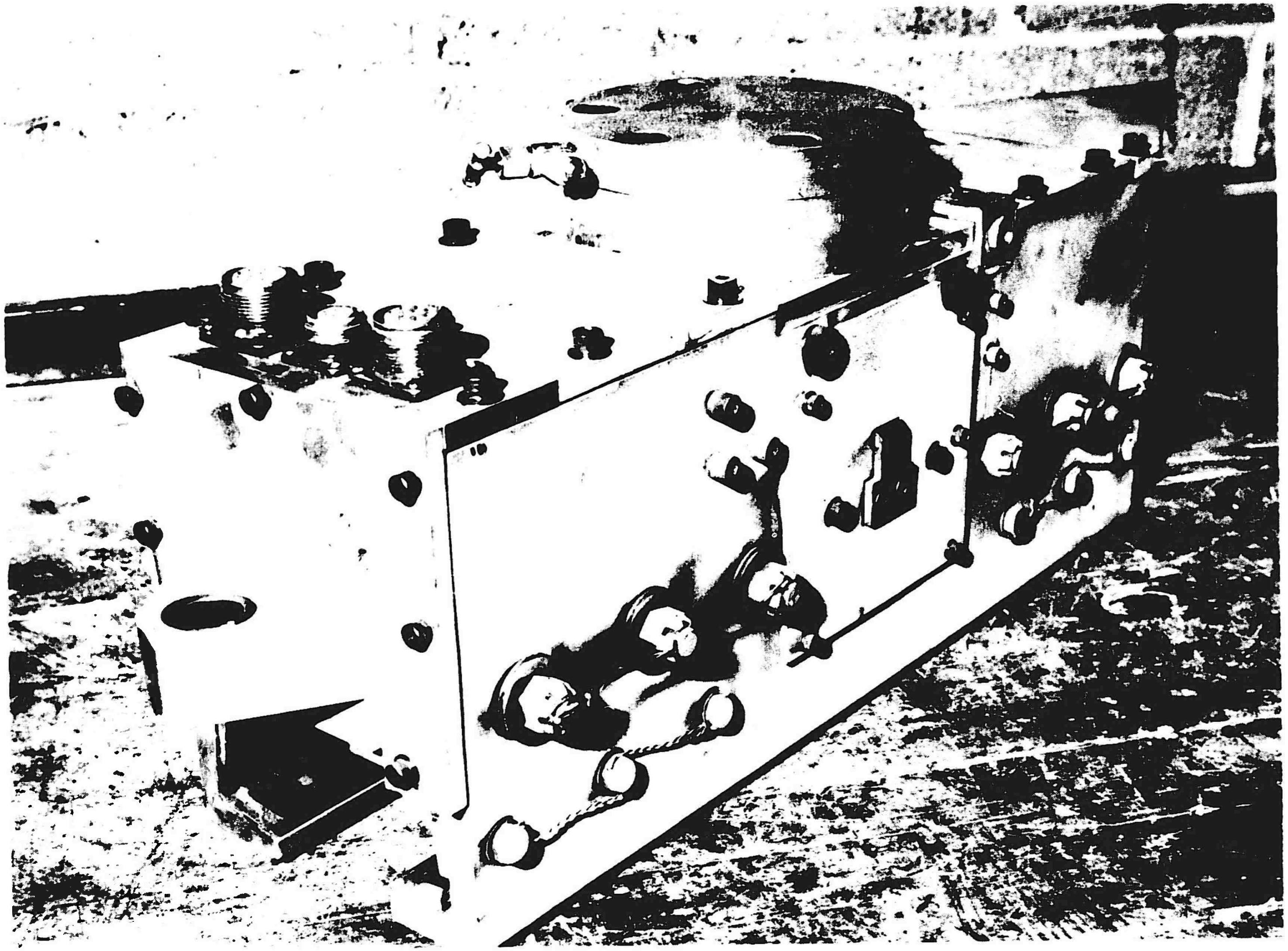

FIGURE 3. SRI Test Slipper After First Three Runs (24-25 April 1958)
Three-quarter Rear View

2. Solid Lubricant Track Coatings

The second major advance in reducing slipper wear is in progress at the Holloman track, and has progressed sufficiently that it is not premature to refer to the results of the track coating program as the second major break-through in reducing slipper wear.

A track coating investigation is one phase of a program which is actually a continuation and extension of the aforementioned work that was conducted at NOTS. The AFMDC program is also an integral part of the current ones in progress at both NOTS and Edwards Air Force Base.

The efforts are based upon and follow the wear theory postulated at the conclusion of the original NOTS-SRI investigation of high-speed sliding friction and wear (Ref. 2).

A tremendous heat flux, on the order of 2,500 cal/cm^2 sec*, exists at the slipper-rail interface (Ref. 2). This heat flux causes and maintains melting of the slipper bearing material, which is the major wear mechanism. The more efficient the dissipation of the heat, the less there is to melt the bearing material. Therefore, it was decided to try to increase the efficiency of the railhead as a heat sink. The rails of current tracks are covered with either original mill scale or rust formed at ambient temperature (Fig. 4). In both cases, the coatings are rather efficient heat barriers. Therefore, part of the program, in conjunction with SRI, was to sandblast 2,000-foot sections of rail, and immediately coat with a layer of a low melting point metallic alloy (Fig. 5, 6, 7, 8, 9, and 10). These metallized coatings were chosen for a variety of reasons, some of which were:

a. To protect the rail from corrosion

b. To conduct heat to the railhead

c. To melt a very thin surface layer and to absorb heat in so doing.

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* 2,500 cal/cm^2 sec is the radiant flux delivered from a black body at a temperature of 6560°K.

FIGURE 4. Railhead Top. Rusted, Unprepared Surface

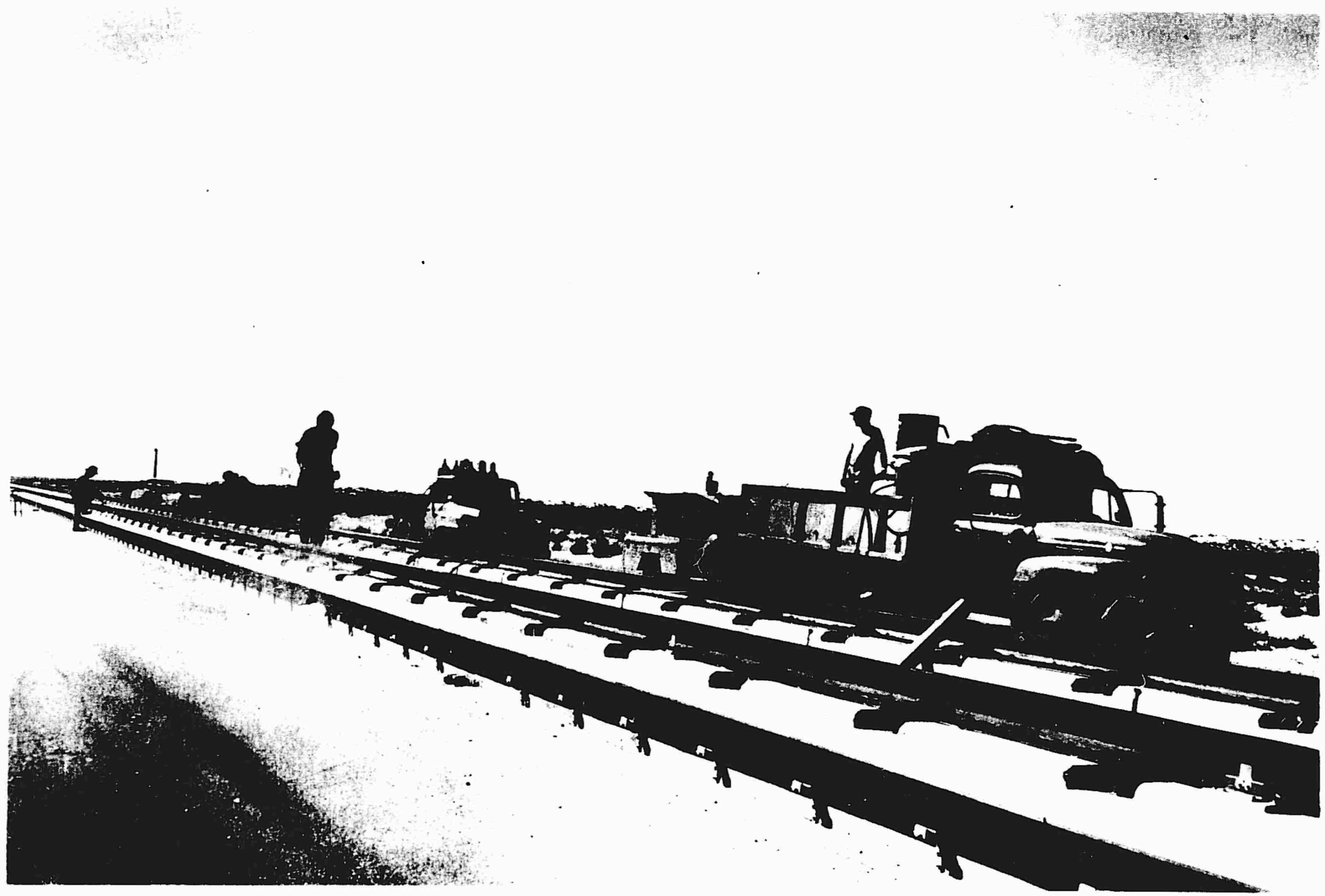


FIGURE 5. Rail Preparation and Metallizing Operations. Left Foreground, Sandblasting; Left Background: Lead Metallizing (right), and Aluminum Metallizing (left)

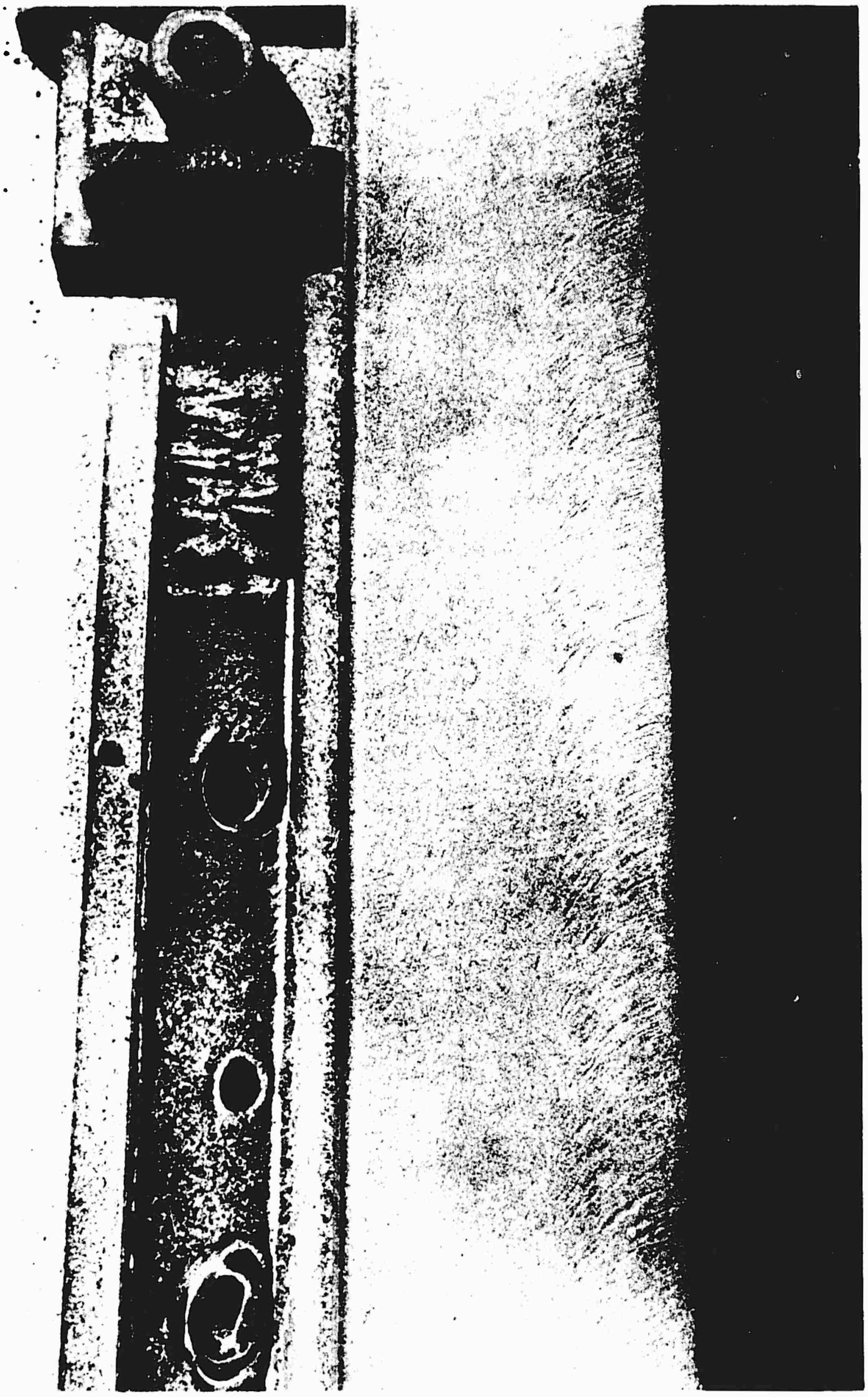


FIGURE 6. Railhead Top, Sandblasted

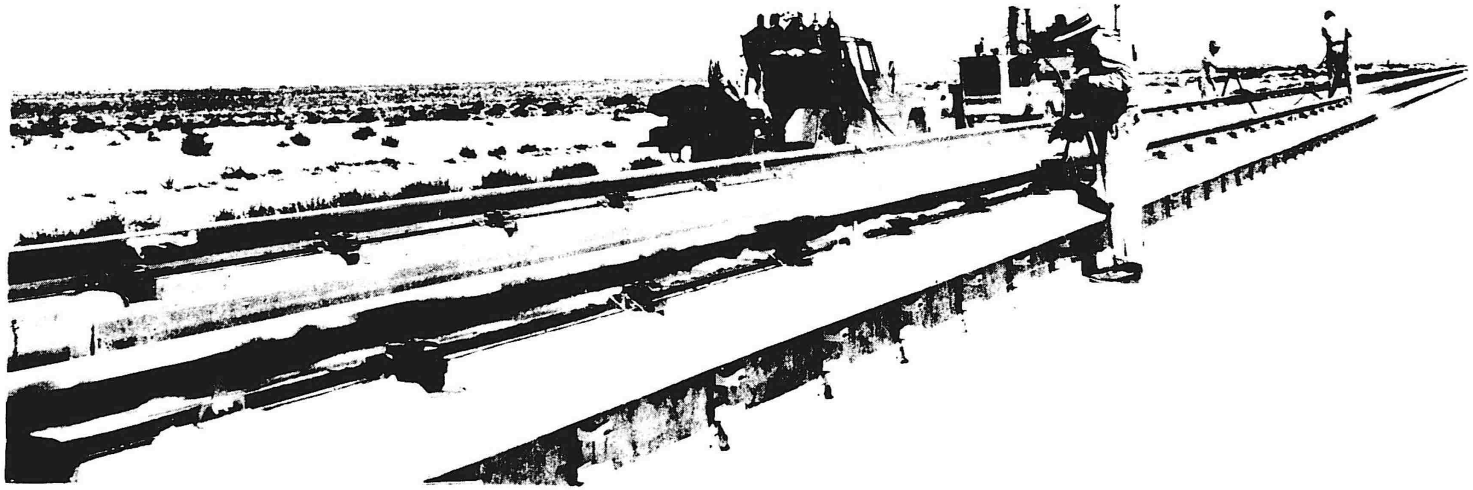


FIGURE 7. Rail Preparation and Metallizing Operations. Foreground: Lead Metallizing (left), and Aluminum Metallizing (right); Right Background, Sandblasting

FIGURE 8. Six Percent Antimonial Lead Metallizing Operation

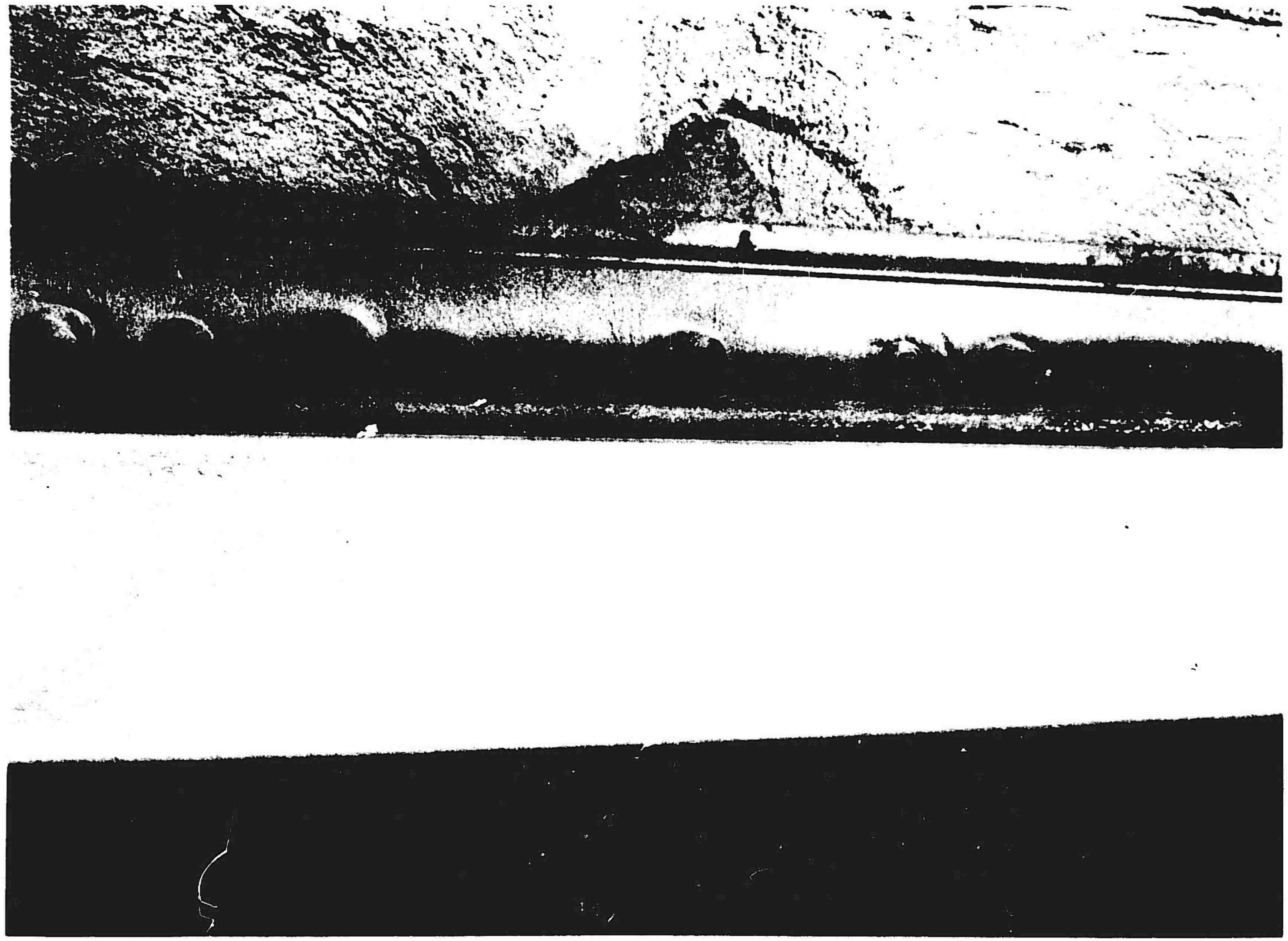


FIGURE 9. Railhead Top, Lead Metallized Coating (undisturbed)

FIGURE 10. Railhead Top, Aluminum Metallized Coating (undisturbed)

II. CONCLUSIONS

The wear rate is time-dependent, increasing progressively from a low initial value toward a steady-state value as time increases. Melting of the bearing material is the primary mechanism of wear (Ref. 2).

As a result of the above postulate, which indicates wear resistance is a function of, among other things, melting point and thermal conductivity, molybdenum, with a melting point of about 4700°F, was tested, and wore one-tenth as much as stainless steel under similar conditions. Consequently the wear resistance of standard inserts was improved by an order of magnitude, and was the first major accomplishment in actually reducing slipper wear (Ref. 2).

There are many standard engineering alloys which show little wear under high-speed sliding conditions at low nominal bearing pressures. But, as the nominal bearing pressures increase, major differences in wear resistance appear. Consequently, excessive wear becomes a problem at high nominal bearing pressures (Ref. 1).

The wear rate of Type 304 stainless steel increases with velocity at nominal bearing pressures above 300 psi. There is no marked difference in the wear rate of molybdenum base alloys tested at 825 and 2400 ft/sec velocity when subjected to nominal bearing pressures between 300 and 1500 psi.

Sections of the track were coated with the following four metallic lubricants: antimonial lead, aluminum, tin base babbitt, and zinc.

Molybdenum bearing samples exhibited a higher wear rate on the lead coating than on bare rail, and lower wear rates on aluminum, babbitt, and zinc. Zinc produced the lowest wear rate of the metallic coatings and resulted in an improvement of at least eight-tenths of an order of magnitude. Type 304 stainless steel bearing samples also exhibited a higher wear rate on the lead coating than on bare rail, and lower wear rates on the remaining three coatings.

A track coating of molybdenum disulfide did not reduce Type 304 stainless steel bearing sample wear. A coating of slaked lime did reduce stainless steel sample wear in comparison with bare rail, by approximately three-quarters of an order of magnitude. Since the slaked lime data were acquired under non-standard conditions (rain), they must be interpreted with caution.

The experimentally proved wear reduction of test samples by rail coatings of metallic zinc, metallic babbitt, and slaked lime, is the second major achievement of the efforts to increase slipper capabilities.

Commercial molybdenum alloys have low impact strength and ductility at ambient temperature. Brittle microconstituents, concentrated in the grain boundaries, appear to be a major cause of depressing the above properties. These microconstituents are controversial, but may be oxides of molybdenum. Attempts are underway to lower the ductile to brittle transformation temperature and raise the recrystallization temperature.

The wear resistance of Type 304 stainless steel and SAE 4140 are similar. The wear resistance of commercially pure vanadium is about one-quarter of an order of magnitude greater than that of stainless steel.

III. TEST PROGRAM

Sixty track tests were made with the SRI test slipper (Fig. 2 and 3). The variables were velocity, bearing material, nominal bearing pressure, and track condition, as listed below:

1. Velocity regime (ft/sec): 825, 1200, and 2,500.

2. Bearing material: Type 304 stainless steel, molybdenum, vanadium, SAE 4140 steel, and tantalum.

3. Nominal bearing pressure (psi): 300, 600, 900, 1200, and 1500.

4. Track condition: Bare (welded joints), bare (pinned joints), aluminum coating, antimonial lead coating, tin base babbitt coating, molybdenum disulfide coating, and slaked lime coating.

Track Test Plan Number 59 was accomplished in April 1958. A modified GAM-67 (AF 5803) sled (Fig. 11, 12, and 13) was used to push two SRI test slippers (one on each rail) at a fairly constant velocity of 825 ft/sec for the 2,000-foot load application distance. Stainless steel and molybdenum test samples were used on bare, unprepared rail. A total of three runs was made.

The second track test series was an interservice cooperative effort by AFMDC and NOTS in June 1958, at the SNORT, under Experiment Specification 4577. The BOMARC sled was used as a pusher vehicle to attain a maximum velocity of 1200 ft/sec. Stainless steel and molybdenum test samples were used, and the load was applied for 10,600 feet of travel on bare, unprepared rail. A total of two runs was made.

FIGURE 11. Rear Three-quarter View of GAM-67 Sled Loaded with Twenty 5.0" HVAR's. Post-fire Condition

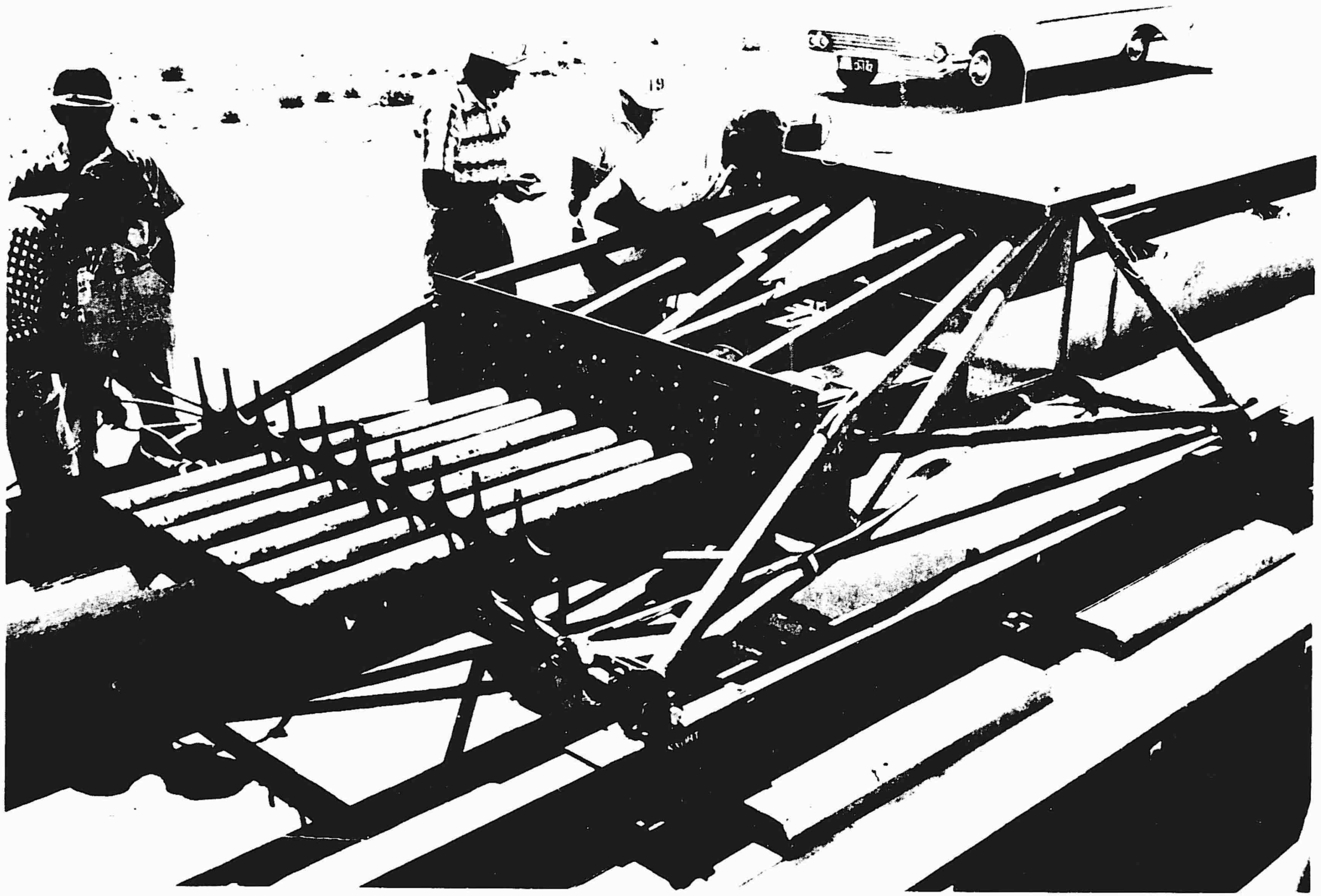


FIGURE 12. Rear Three-quarter View of GAM-67 Sled, Partially Unloaded. Post-fire Condition

Note linkage above right front slipper for connection with SRI test slipper.

FIGURE 13. Linkage Above a Front Slipper of the GAM-67 Sled for Connection with SRI Test Slipper

Track Test Plan Number 79 was accomplished in August 1958. A Viper Monorail sled (Fig. 14) was used to push an SRI test slipper to a maximum velocity of about 2,500 ft/sec. Stainless steel and molybdenum test samples were used again, and the load was applied for 2,000 feet of travel on bare, unprepared rail. A total of six runs was made.

Track Test Plan Number 91 was started in September and completed in October 1958. The top surfaces of 2,000 feet of both rails were sandblasted and metallized. The operations were performed by SRI subcontractors. Both rails were metallized from Track Station 11,030 to Track Station 13,030 in less than three days. The east rail was coated with aluminum, and the west rail with 6 percent antimonial lead. The SRI test slippers were again pushed with Viper Monorail sleds as above. Five stainless steel and three molybdenum test samples were run on the aluminum track coating, and two stainless steel and two molybdenum test samples on the lead coating. A total of twelve runs was made.

Track Test Plan Number 101 was accomplished in November 1958. The top surfaces of another 2,000 feet of both rails were sandblasted and metallized. Both rails were metallized from Track Station 13,030 to Track Station 15,030. The east rail was metallized with zinc and the west rail with tin base babbitt. The test item and propulsion system were the same as above. Four stainless steel and three molybdenum test samples were run on the zinc track coating, and four stainless steel and two molybdenum test samples on the tin base babbitt; one stainless steel test sample was run on bare rail. A total of fourteen runs was made.

Track Test Plan Number 116 was started in March and completed in April 1959. The top surface of the east rail was coated with molybdenum disulfide powder between Track Station 9,000 and Track Station 11,000. The molybdenum disulfide was obtained through the courtesy of the National Aluminate Corporation in stick form (Fig. 15), and was applied by towing the "Molly" applicator (Fig. 16, 17, 18, and 19) over the test rail section six times. The top surface of the west rail was coated with slaked lime between the same track stations. Hydrated lime $Ca(OH)_2$ was suspended in tap water, applied to the railhead with a standard paint spray gun, and air dried. The test item and propulsion system were the same as above. Seven stainless steel, two vanadium, and three SAE 4140 steel test samples were run on the original five-month old zinc coating. Three stainless steel test samples were run on the molybdenum disulfide coating, and one tantalum sample on bare rail. The experimental work was concluded with four stainless steel samples tested on the slaked lime coating. A total of twenty-three runs was made.

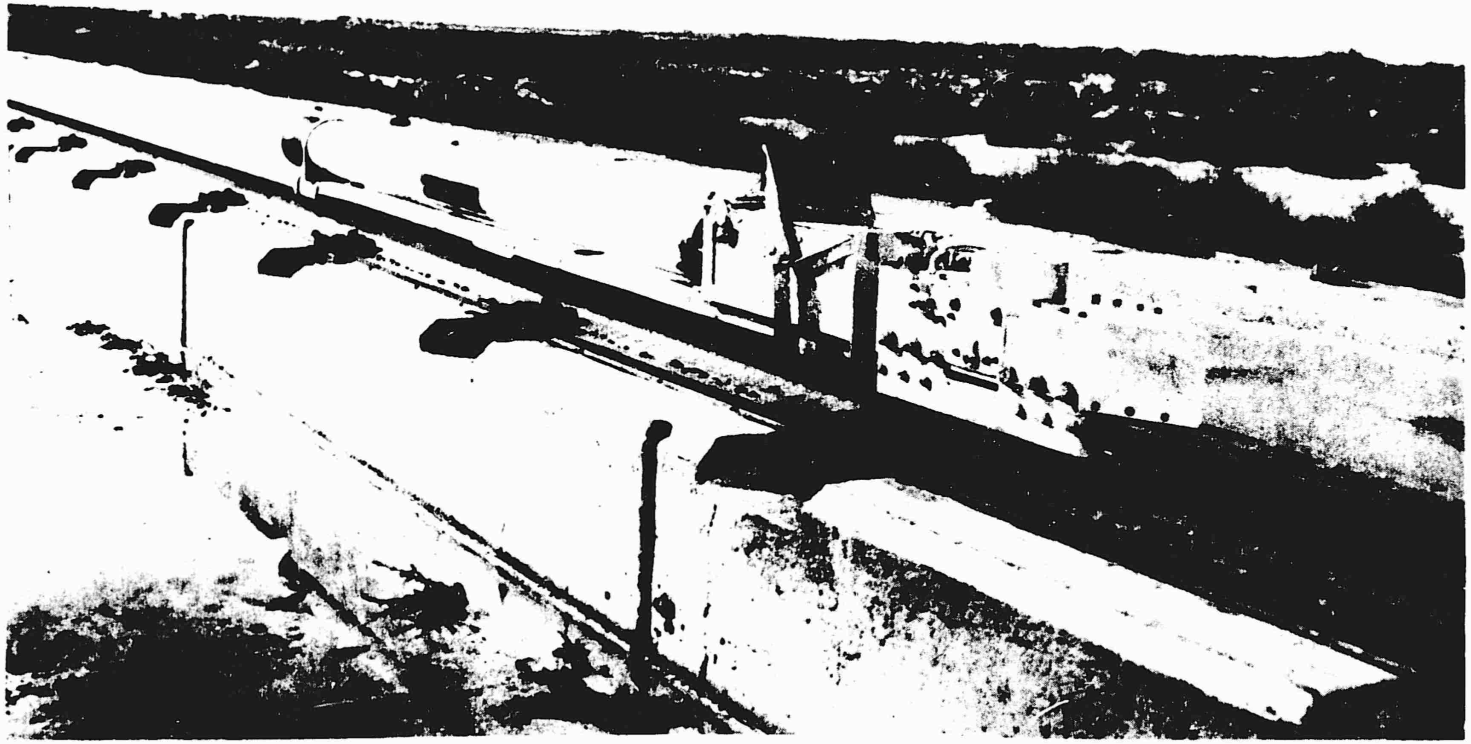


FIGURE 14. Three-quarter Front View of SRI Test Slipper and Viper Monorail Sled. Post-fire Condition

Note actuated air brake.

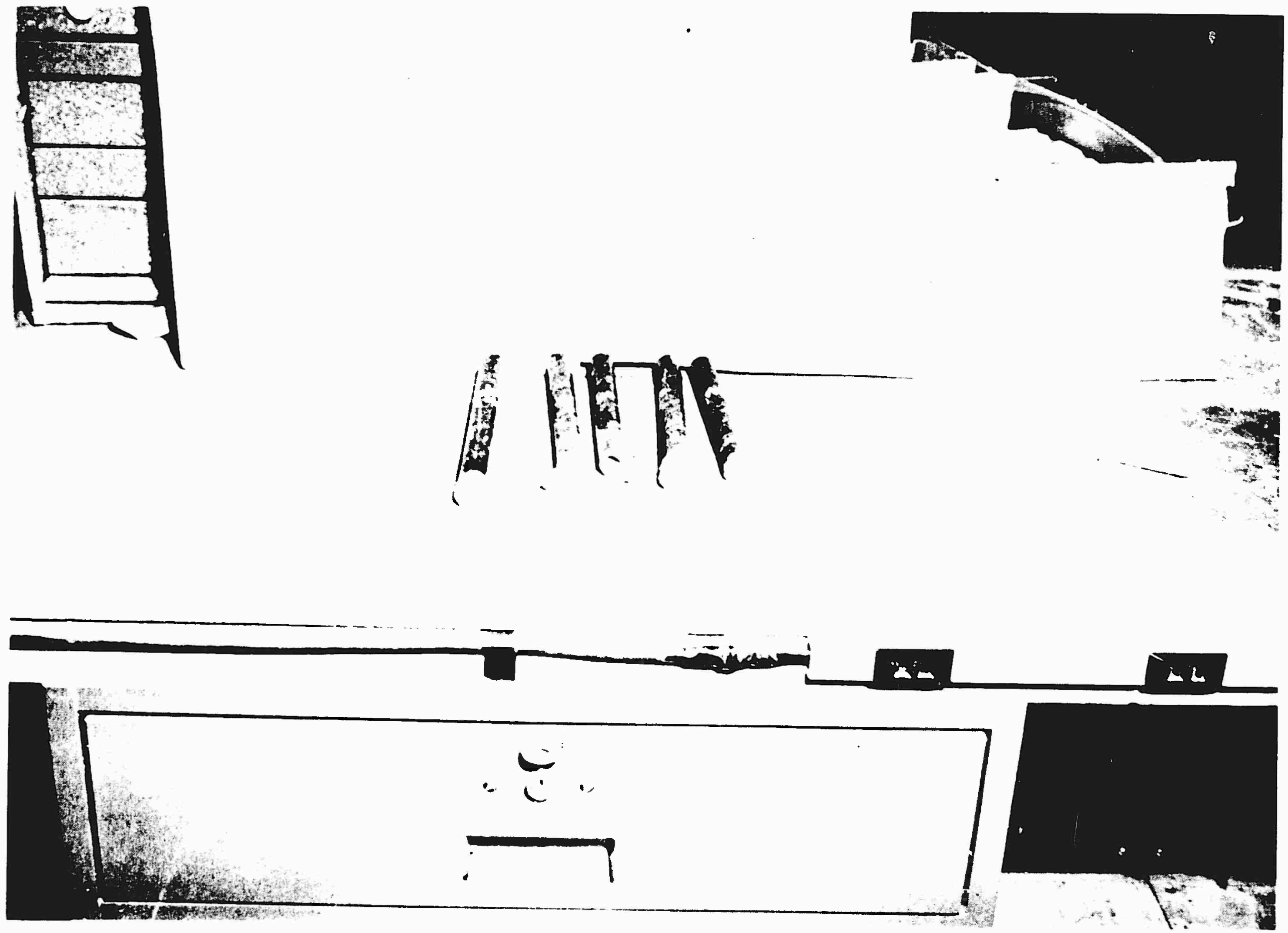


FIGURE 15. Nalco Lubricator (Molybdenum Disulfide) Sticks
Extreme left, new; remaining four, used.

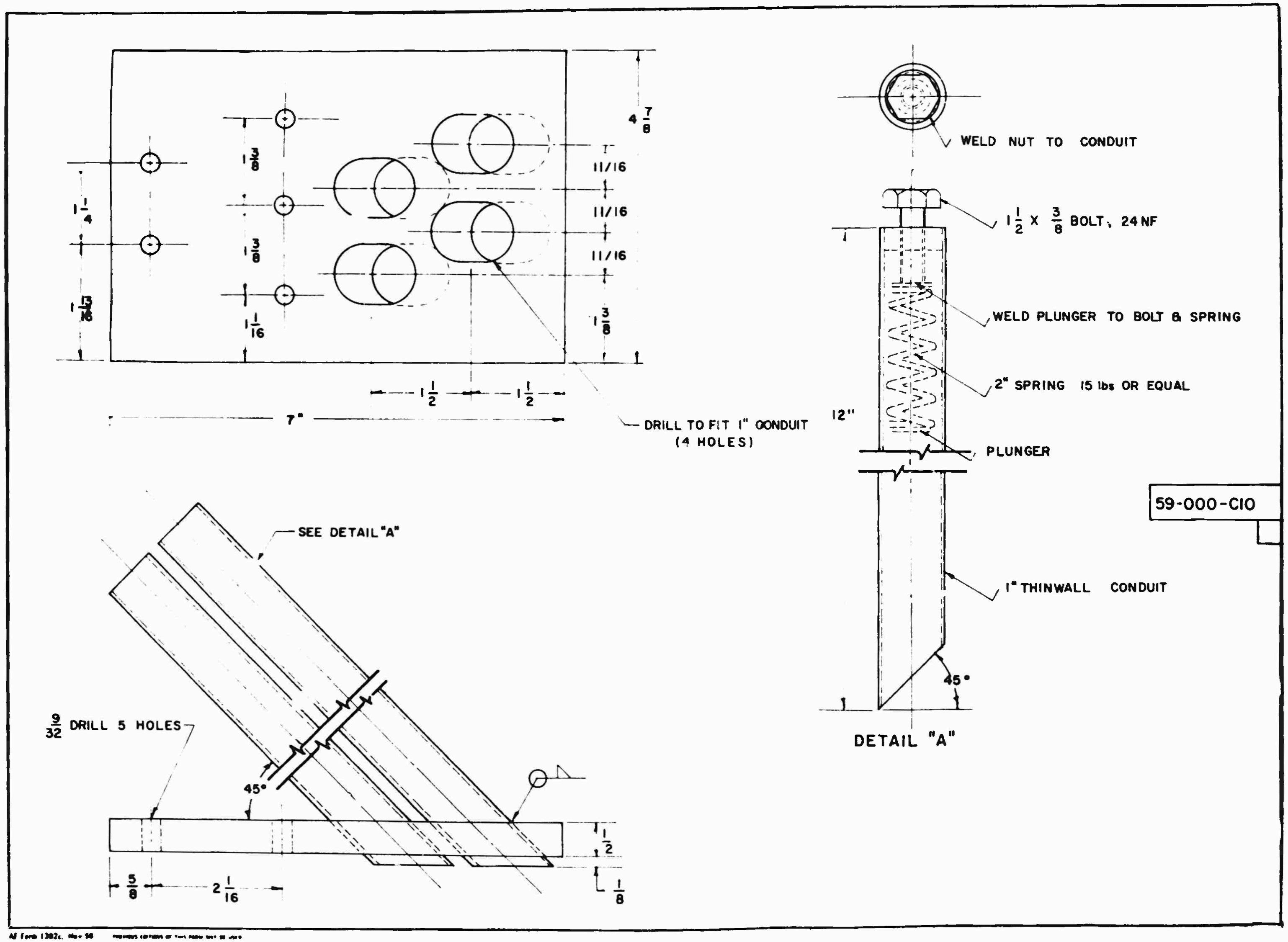


FIGURE 16. Nalco Lubrication Holder

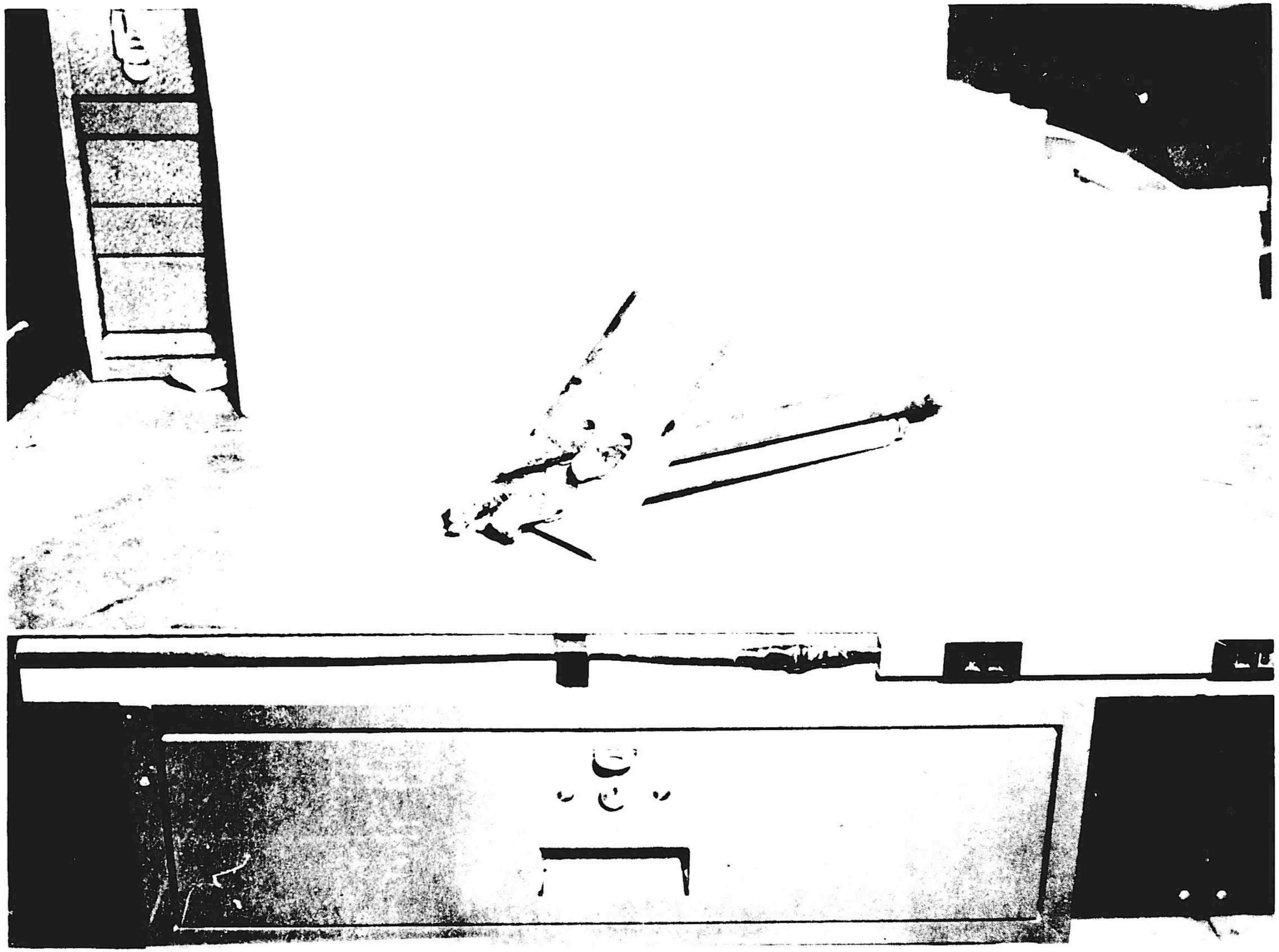


FIGURE 17. Nalco Lubrication Holder with Nalco Lubricator Sticks After Use

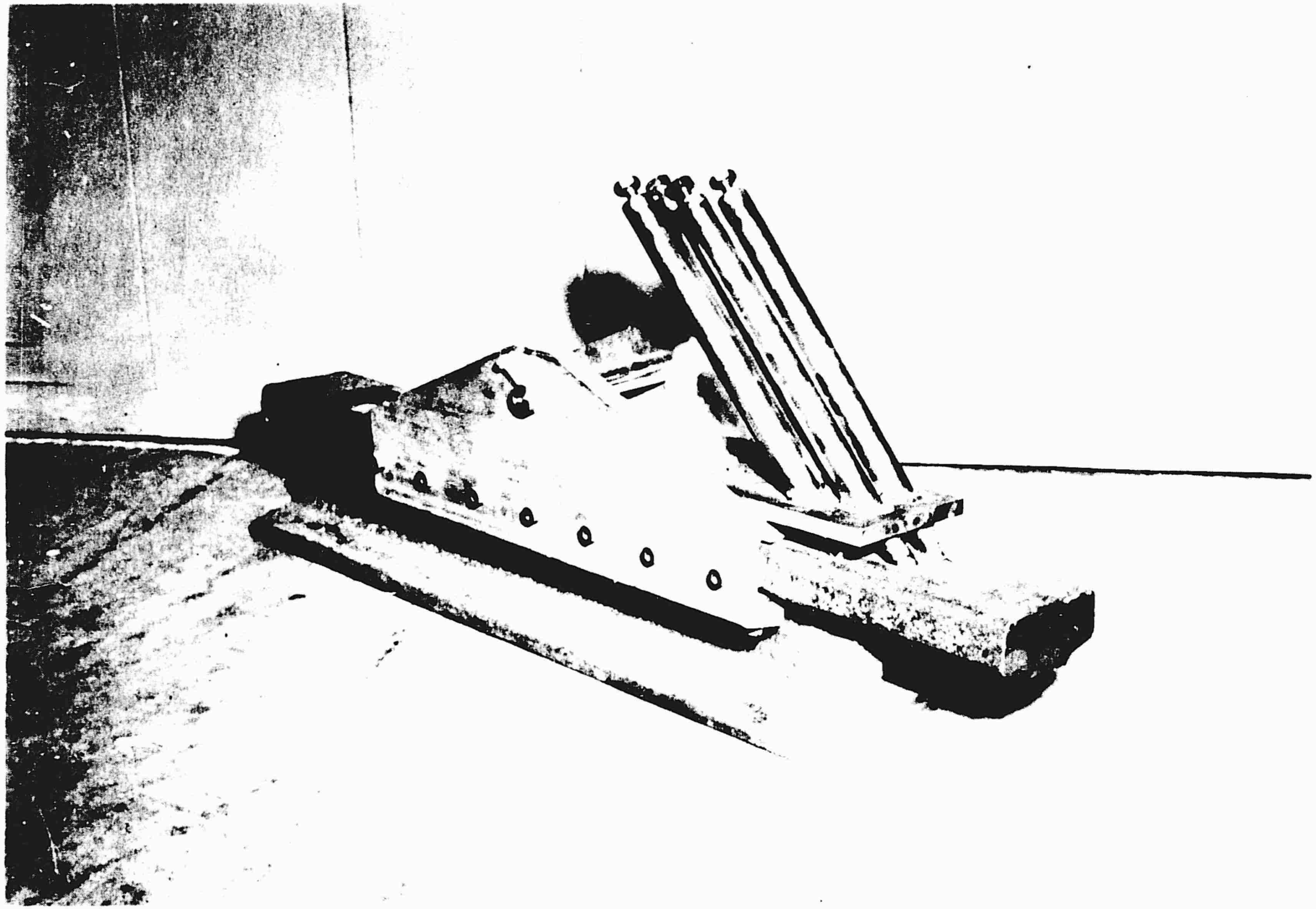


FIGURE 18. Three-quarter Rear View of Nalco Lubrication Holder with Nalco Lubricator Sticks Attached to Drag Slipper

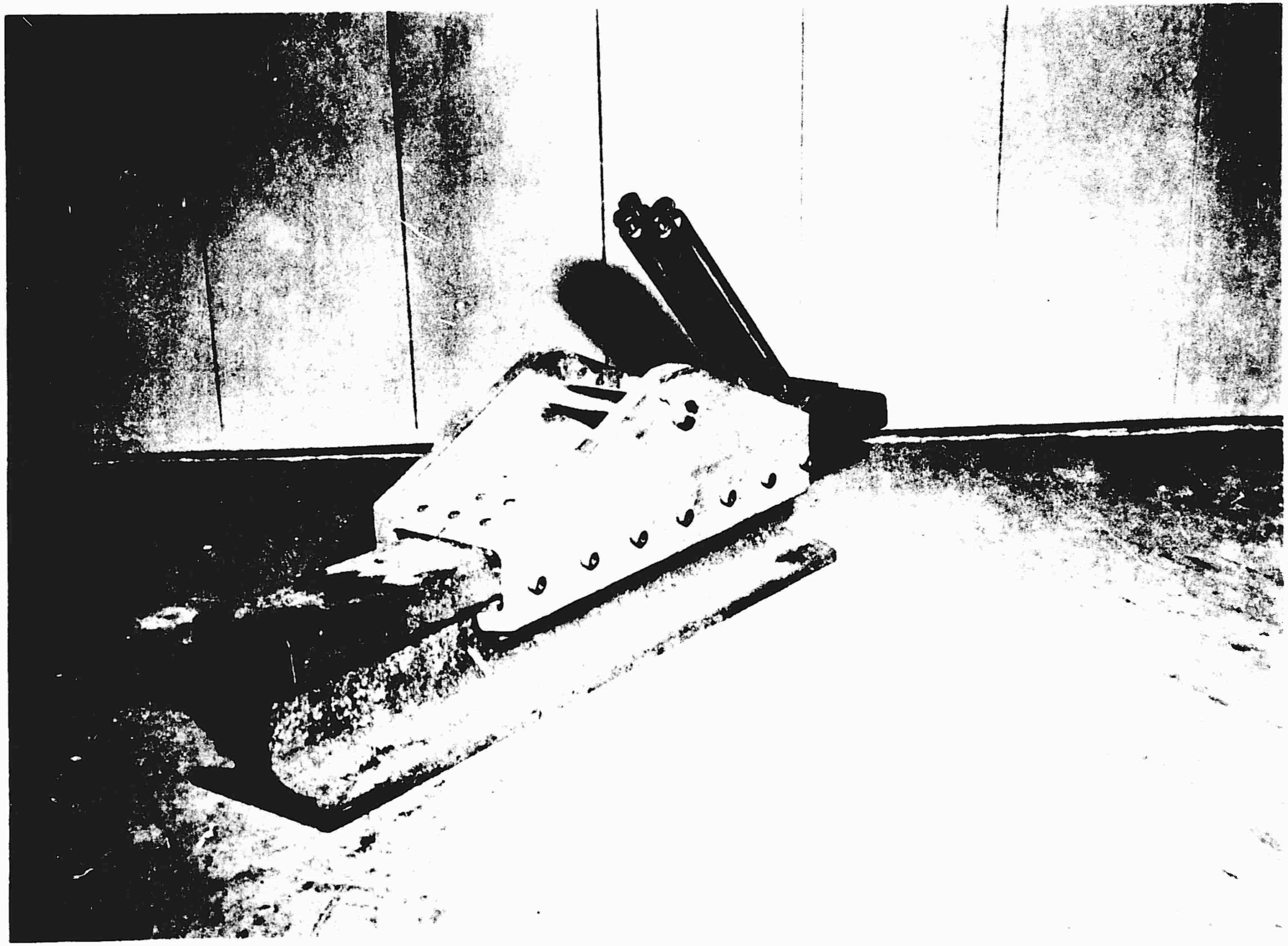


FIGURE 19. Three-quarter Front View of Nalco Lubrication Holder with Nalco Lubricator Sticks Attached to Drag Slipper

IV. TEST RESULTS

The experimental conditions and data have been summarized, and are presented in the table below.

Run No.	Date	Sample	Distance Load Application (ft)	Bearing Pressure (psi)	Velocity Regime (ft/sec)	Linear Wear (in.)	Average Wear Rate (in./ft)	Rail Condition
1	24 Apr 58	SS[1]	2,000	300	825	0.019	9.5×10^{-6}	Bare (welded joints)[4]
		Mo[2]	2,000	300	825	0.004	2×10^{-6}	Bare (welded joints)
2	25 Apr 58	SS	2,000	900	825	0.14	7×10^{-5}	Bare (welded joints)
		Mo[2]	2,000	900	825	0.015	7.5×10^{-6}	Bare (welded joints)
3	25 Apr 58	SS	2,000	1,500	825	0.392	1.96×10^{-4}	Bare (welded joints)
		Mo[2]	2,000	1,500	825	0.027	1.35×10^{-5}	Bare (welded joints)
4	12 Jun 58			Test sample failed to load				Bare (pinned joints)[5]
5	13 Jun 58	SS	10,600	600	1,200	0.42+[8]	3.9×10^{-5}	Bare (pinned joints)
		Mo[2]	10,600	1,200	1,200	0.054	5×10^{-6}	Bare (pinned joints)
6	21 Aug 58	SS	2,000	300	2,500	0.015	7.5×10^{-6}	Bare (welded joints)
7	21 Aug 58	Mo[2]	2,000	300	2,500	0.003	1.5×10^{-6}	Bare (welded joints)
8	21 Aug 58	Mo[2]	2,000	900	2,500	0.020	1×10^{-5}	Bare (welded joints)
9	22 Aug 58	SS		Test sample failed to load				Bare (welded joints)
10	22 Aug 58	SS	2,000	900	2,500	0.356+[8]	1.78×10^{-4}	Bare (welded joints)
11	22 Aug 58	Mo[2]	2,000	1,500	2,500	0.035	1.75×10^{-5}	Bare (welded joints)
12	26 Sep 58	SS	2,000	300	2,500	0.009	4.5×10^{-6}	Aluminum coated (welded joints)[6]
13	29 Sep 58	SS	2,000	600	2,500	0.025	1.25×10^{-5}	Aluminum coated (welded joints)

Run No.	Date	Sample	Distance Load Application (ft)	Bearing Pressure (psi)	Velocity Regime (ft/sec)	Linear Wear (in.)	Average Wear Rate (in./ft)	Rail Condition
14	29 Sep 58	SS	2,000	300	2,500	0.070	3.5×10^{-5}	Lead coated (welded joints)[7]
15	29 Sep 58	SS	2,000	600	2,500	0.130	6.5×10^{-5}	Lead coated (welded joints)
16	29 Sep 58	SS	2,000	900	2,500	Test sample failed to load		Aluminum coated (welded joints)
17	30 Sep 58	Mo^2	2,000	900	2,500	0.038	1.9×10^{-5}	Lead coated (welded joints)
18	30 Sep 58	Mo^2	2,000	900	2,500	Test sample failed to load		Aluminum coated (welded joints)
19	1 Oct 58	SS	2,000	900	2,500	Test sample failed to load		Aluminum coated (welded joints)
20	1 Oct 58	Mo^2	2,000	1,500	2,500	0.042	2.1×10^{-5}	Lead coated (welded joints)
21	1 Oct 58	Mo^3	2,000	1,500	2,500	0.014	7×10^{-6}	Aluminum coated (welded joints)
22	2 Oct 58	SS	2,000	900	2,500	0.167 Wear data obtained from record	8.3×10^{-5}	Aluminum coated (welded joints)
23	2 Oct 58	Mo^3	2,000	900	2,500	0.004	2×10^{-6}	Aluminum coated (welded joints)
24	14 Nov 58	SS	2,000	300	2,500	0.013	6×10^{-6}	Babbitt coated (welded joints)[9]
25	14 Nov 58	SS	2,000	300	2,500	0.008	4×10^{-6}	Zinc coated (welded joints)[10]

Run No.	Date	Sample	Distance Load Application (ft)	Bearing Pressure (psi)	Velocity Regime (ft/sec)	Linear Wear (in.)	Average Wear Rate (in./ft)	Rail Condition
26	17 Nov 58	SS	2,000	600	2,500	0.026	1.3×10^{-5}	Babbitt coated (welded joints)
27	17 Nov 58	SS	2,000	600	2,500	0.025	1.2×10^{-5}	Zinc coated (welded joints)
28	17 Nov 58	SS	---	900	2,500	Unloading malfunction		Babbitt coated (welded joints)
29	17 Nov 58	Mo[2]	2,000	900	2,500	0.005	2×10^{-6}	Zinc coated (welded joints)
30	18 Nov 58	SS	2,000	900	2,500	0.069	3.4×10^{-5}	Babbitt coated (welded joints)
31	18 Nov 58	SS	---	900	2,500	Unloading malfunction		Zinc coated (welded joints)
32	18 Nov 58	Mo[2]	2,000	900	2,500	0.004	2×10^{-6}	Babbitt coated (welded joints)
33	18 Nov 58	SS	2,000	900	2,500	0.101	5.0×10^{-5}	Zinc coated (welded joints)
34	21 Nov 58	Mo[3]	2,000	1,500	2,500	0.008	4×10^{-6}	Babbitt coated (welded joints)
35	21 Nov 58	Mo[3]	---	1,500	2,500	Test sample failed to load		Zinc coated (welded joints)
36	24 Nov 58	SS	2,000	600	2,500	0.132	6.6×10^{-5}	Bare (welded joints)
37	28 Nov 58	Mo[3]	2,000	1,500	2,500	0.006	3×10^{-6}	Zinc coated (welded joints)

Run No.	Date	Sample	Distance Load Application (ft)	Bearing Pressure (psi)	Velocity Regime (ft/sec)	Linear Wear (in.)	Average Wear Rate (in./ft)	Rail Condition
38	30 Mar 59	SS	Malfunction; guillotine did not fire, knife blade grounded					Zinc coated (welded joints)
39	30 Mar 59	SS	2,000	600	2,500	0.069	3.5×10^{-5}	Zinc coated (welded joints)
40	30 Mar 59	SS	2,000	900	2,500	0.092	4.6×10^{-5}	Zinc coated (welded joints)
41	30 Mar 59	SS	Malfunction; guillotine did not fire, sled wiring shorted					Zinc coated (welded joints)
42	31 Mar 59	V[11]	2,000	900	2,500	0.066	3.3×10^{-5}	Zinc coated (welded joints)
43	31 Mar 59	V	2,000	1,500	2,500	0.137	6.8×10^{-5}	Zinc coated (welded joints)
44	1 Apr 59	SS	2,000	600	2,500	0.048	2.4×10^{-5}	Zinc coated (welded joints)
45	1 Apr 59	4140	19,000 Malfunction; sample did not unload	900	2,500 to stop	0.277+	1.5×10^{-5}	2,000 feet on zinc coated, 17,000 feet on bare (welded joints)
46	2 Apr 59	SS	2,000	300	2,500	0.013	6.5×10^{-6}	Zinc coated (welded joints)
47	2 Apr 59	4140	15,000 Malfunction; sample did not unload. Knife blade shorted when folded back.	300	2,500 to stop	0.120	8×10^{-6}	2,000 feet on zinc coated, 13,000 feet on bare (welded joints)

Run No.	Date	Sample	Distance Load Application (ft)	Bearing Pressure (psi)	Velocity Regime (ft/sec)	Linear Wear (in.)	Average Wear Rate (in./ft)	Rail Condition
48	2 Apr 59	4140	2,000	600	2,500	0.045	2.3×10^{-5}	Zinc coated (welded joints)
49	2 Apr 59	SS	2,000	600 (heavy spring)	2,500	0.095	4.8×10^{-5}	Zinc coated (welded joints)
50	3 Apr 59	SS	2,000	600	2,500	0.040	2×10^{-5}	Babbitt coated (welded joints)
51	3 Apr 59	SS	2,000	900	2,500	0.177	8.8×10^{-5}	Babbitt coated (welded joints)
52	3 Apr 59	SS	2,000	300	2,500	0.029	1.5×10^{-5}	Babbitt coated (welded joints)
53	6 Apr 59	SS	2,000	600	2,500	0.143	7×10^{-5}	MoS_2 coated (welded joints)
54	6 Apr 59	SS	Malfunction; sample did not load, pin and pawl jammed, motor separated from sled					MoS_2 coated (welded joints)
55	6 Apr 59	SS	2,000 Wear exceeded gauge length	900	2,500	0.344	1.7×10^{-4}	MoS_2 coated (welded joints)
56	6 Apr 59	Ta welded to Mo	2,000	900 (Ta to Mo weld failure suspected)	2,500	0.100	5×10^{-5}	Bare (welded joints)
57	7 Apr 59	SS	2,000	600	2,500 (fresh coating)	0.020 (rained during lime spraying)	1×10^{-5}	Slaked lime coating (welded joints)

Run No.	Date	Sample	Distance Load Application (ft)	Bearing Pressure (psi)	Velocity Regime (ft/sec)	Linear Wear (in.)	Average Wear Rate (in./ft)	Rail Condition
58	7 Apr 59	SS	2,000	900	2,500 (2nd run on coating)	0.075 (rained during test)	3.7×10^{-5}	Slaked lime coating (welded joints)
59	7 Apr 59	SS	Malfunction; sample did not load					Slaked lime coating (welded joints)
60	8 Apr 59	SS	2,000	300	2,500 (fresh coating)	0.006	3×10^{-6}	Slaked lime coating (welded joints)

Footnotes:
1. Type 304 stainless steel
2. Commercially pure molybdenum
3. 0.5 percent titanium in molybdenum
4. AFMDC track, unprepared surface
5. SNORT, unprepared surface
6. AFMDC track, sandblasted and metallized with aluminum
7. AFMDC track, sandblasted and metallized with 6 percent antimonial lead
8. Wear equal to entire gauge length
9. AFMDC track, sandblasted and metallized with tin base babbitt
10. AFMDC track, sandblasted and metallized with zinc
11. Commercially pure vanadium

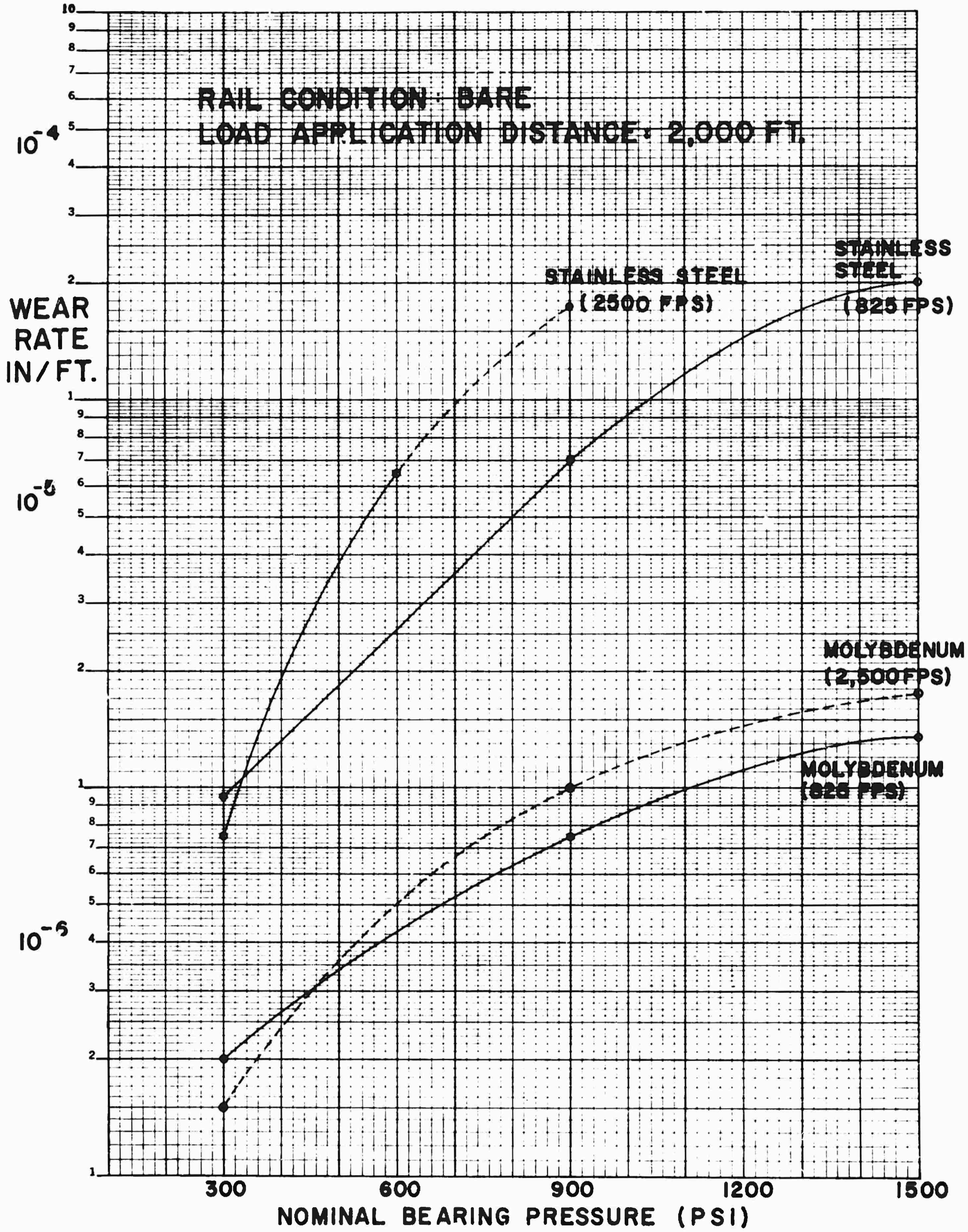

RAIL CONDITION: BARE
LOAD APPLICATION DISTANCE: 2,000 FT.
WEAR RATE IN/FT.
10^{-4}
10^{-5}
10^{-6}
STAINLESS STEEL (2500 FPS)
STAINLESS STEEL (825 FPS)
MOLYBDENUM (2,500 FPS)
MOLYBDENUM (825 FPS)
300
600
900
1200
1500
NOMINAL BEARING PRESSURE (PSI)

FIGURE 20

V. DATA DISCUSSION

Wear rate versus nominal bearing pressure curves have been plotted for bare rail conditions (Fig. 20). The four curves represent six tests with Type 304 stainless steel and six tests with commercially pure molybdenum. The data for two of the curves were obtained at a fairly constant velocity of 825 ft/sec, and for the remaining two curves at 2,400 ft/sec ± 150. The 900 psi data point on the high-speed stainless steel plot is a minimum wear rate because the entire gauge length of the test sample was worn through.

The two stainless steel curves (Fig. 20) indicate the wear rate of stainless steel increases with velocity at nominal bearing pressures above 300 psi. This observation is qualitatively substantiated by visual inspection of the bearing inserts of the SRI test slippers. They also wear more during high-speed runs than during low-speed runs. The difference in wear rate of the two molybdenum base alloy curves is not marked; therefore, at this time it is concluded that the wear rate of molybdenum is independent of velocity between 825 and 2,500 ft/sec within 300 to 1500 psi nominal bearing pressure. It appears that the increased heat flux at higher velocity is not sufficient to establish the steady state wear condition in molybdenum (Ref. 2).

The current AFMDC-SRI program is complementary to the NOTS-SRI friction and wear programs. The two tests on SNORT in June 1958 were an effort to establish a base for correlation of data collected at the two tracks with both the Air Force-SRI and Navy-SRI test slippers. Unfortunately, the total wear of the test sample in the Air Force-SRI test slippers was considerably greater than that in the Navy-SRI test slippers. In addition, the supports on the Air Force-SRI test slippers were damaged by heat, which did not occur on the Navy-SRI slippers. It is felt the above occurrences were caused by differences in aerodynamic cooling, which has been reduced in the Air Force-SRI slippers by a vertical wedge nose with lower drag for testing at supersonic velocity.

Molybdenum bearing samples have been tested on four different metallic coatings. Figure 21 indicates a higher wear rate on the antimonial lead coating than on bare rail. The lead coated rail caused an erosive condition, as noted in Figures 22, 23, and 24. Figure 21 also indicates a lower wear rate on the aluminum, babbitt, and zinc coatings than on the bare rail. The molybdenum samples wore the least on the zinc coating, and exhibited a reduction in wear of at least 80 percent, based on bare rail behavior.

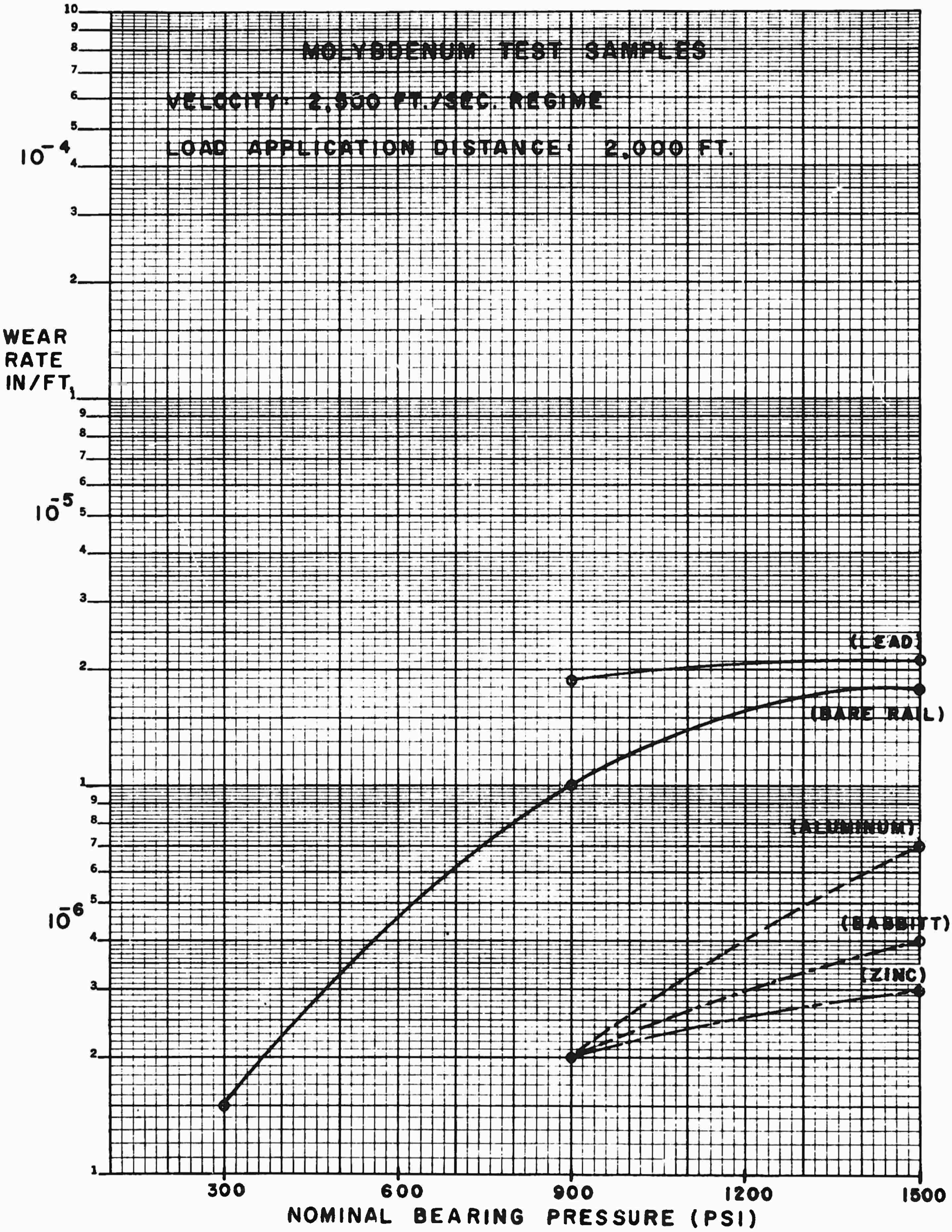

MOLYBDENUM TEST SAMPLES
VELOCITY: 2,500 FT./SEC. REGIME
LOAD APPLICATION DISTANCE: 2,000 FT.
WEAR RATE IN/FT
10^{-4}
10^{-5}
10^{-6}
(LEAD)
(BARE RAIL)
(ALUMINUM)
(BABBITT)
(ZINC)
300
600
900
1200
1500
NOMINAL BEARING PRESSURE (PSI)

FIGURE 21

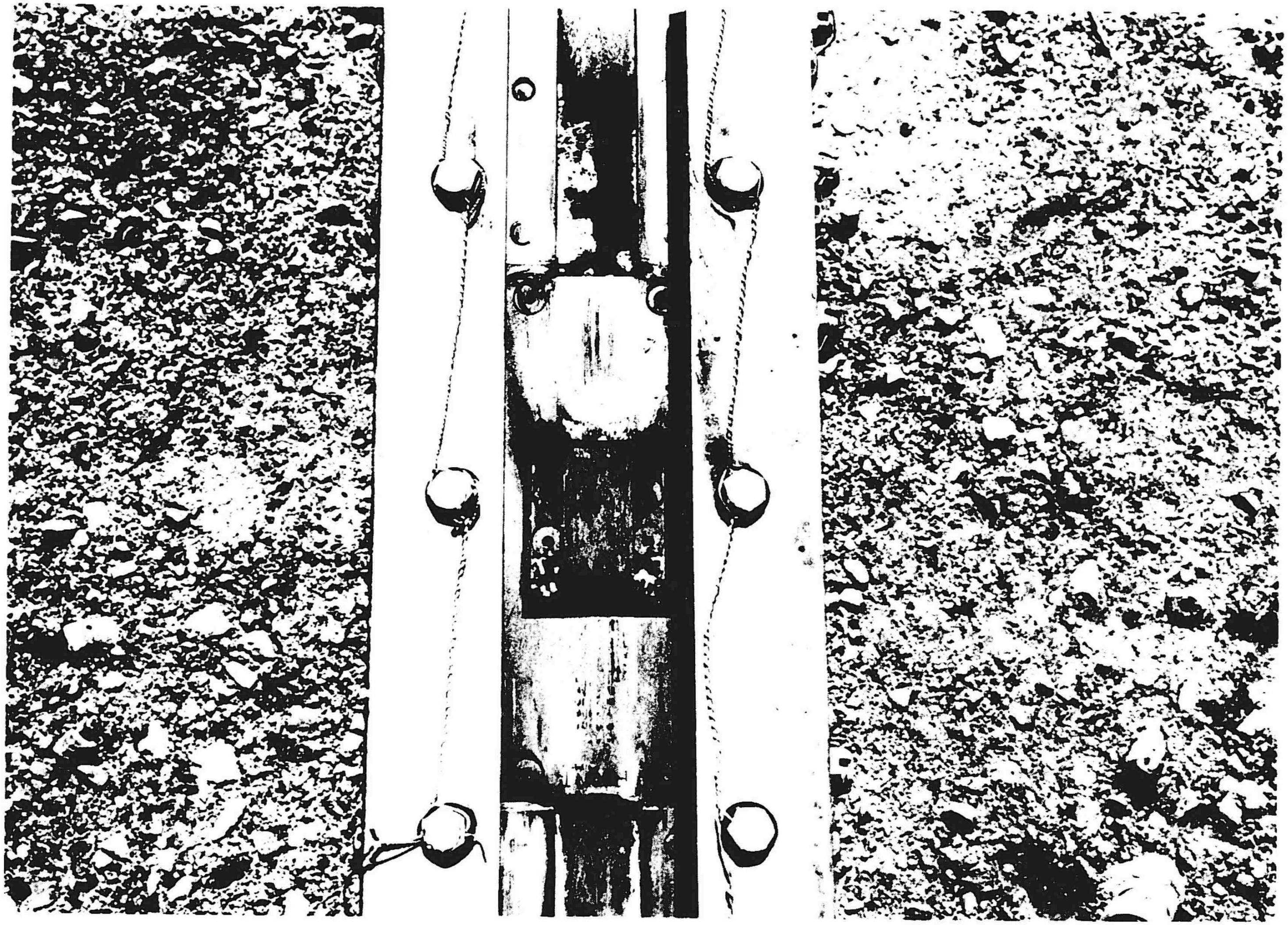


FIGURE 22. Top Bearing Surface of SRI Test Slipper After Lead Coating Test

Note fractured sample holder, and erosion caused by lead.

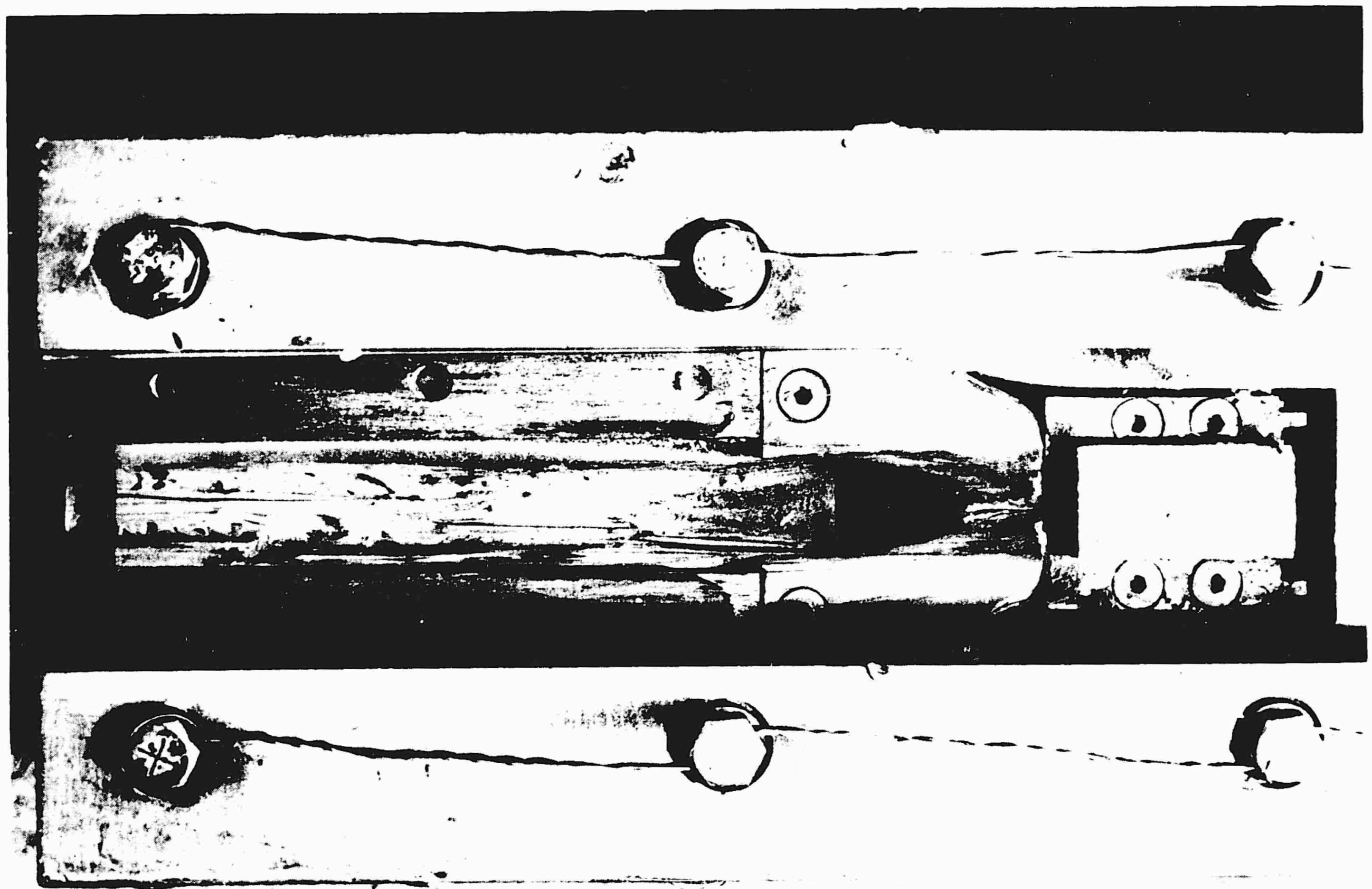
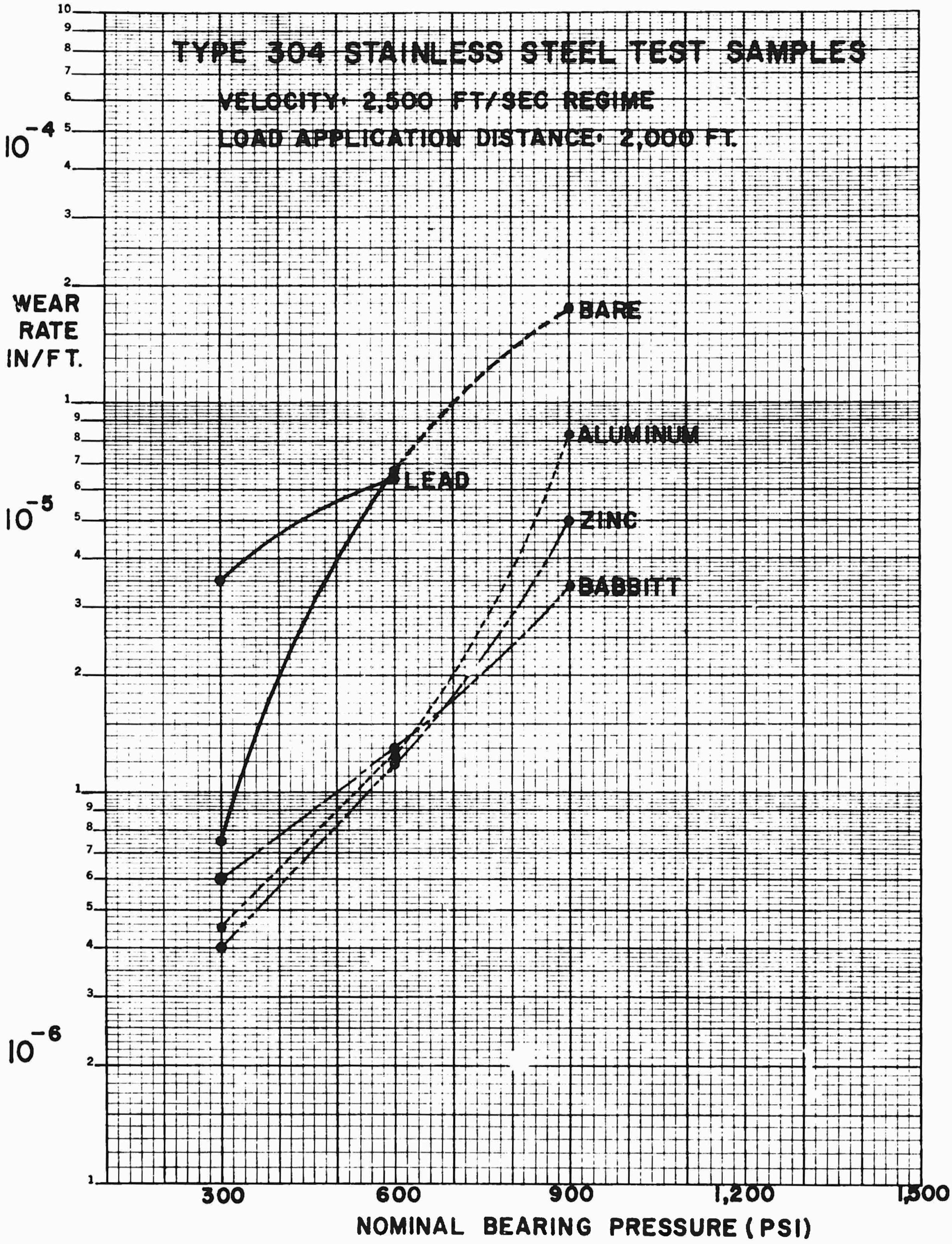


FIGURE 23. Top Bearing Surface of SRI Test Slipper After Lead Coating Test
Note erosion caused by lead.

FIGURE 24. Top Bearing Surface of SRI Test Slipper After Lead Coating Test

Note erosion caused by lead.



TYPE 304 STAINLESS STEEL TEST SAMPLES
VELOCITY: 2,500 FT/SEC REGIME
LOAD APPLICATION DISTANCE: 2,000 FT.
WEAR RATE IN/FT.
10⁻⁴
10⁻⁵
10⁻⁶
BARE
ALUMINUM
LEAD
ZINC
BABBITT
300
600
900
1,200
1,500
NOMINAL BEARING PRESSURE (PSI)

FIGURE 25

Stainless steel bearing samples have also been tested on the metallic coatings. Figure 25 indicates no reduction in wear by the antimonial lead. The erosive action noted in Figures 22, 23, and 24 prevailed. Figure 25 also indicates a lower wear rate on the aluminum, babbitt, and zinc coatings than on the bare rail. The wear rates of stainless steel on the latter three coatings are quite similar.

The aluminum coating had very poor adherence to the rail, and some scraped off and bound the monorail sled during towing; but at high speed it did reduce sample wear appreciably. However, its poor adherence made it economically and operationally impractical (Fig. 26, 27, 28, 29, and 30).

The zinc and babbitt coatings were tested a second time after almost five months of weathering. During the aging period nine sleds were run over the zinc coated rail sections and twenty-four sleds over the babbitt. The wear reducing capability of both coatings dropped somewhat as indicated in Figure 31; the babbitt more than the zinc.

Stainless steel bearing samples have also been tested on two nonmetallic coatings: molybdenum disulfide and slaked lime. Figure 32 illustrates that stainless steel wears the same amount on bare rail as on molybdenum disulfide at 600 psi nominal bearing pressure. The 900 psi samples were worn through their entire gauge length during both the bare rail and molybdenum disulfide tests. Therefore, the 900 psi data points represent minimum wear rates with the possibility that the true wear rate figures are higher. At any rate, the molybdenum disulfide coating apparently did not reduce test sample wear. A possible explanation for this lack of improvement is that the high-lubricity molybdenum disulfide oxidized to form the abrasive oxides of molybdenum. This reaction occurs rapidly at temperatures in excess of 1050°F. It is also possible that the apparent failure of molybdenum disulfide to reduce wear was caused by the method of application. A bonded coating was not attained because it was applied in dry powder form rather than suspended in an adherent liquid vehicle.

The slaked lime curve (Fig. 32) indicates a considerable reduction of wear rate in comparison with the bare rail condition.

The first test was made at 600 psi nominal bearing pressure. The bulk of the coating was scraped off, but a second test sample was run over the original coating at 900 psi nominal bearing pressure to check life expectancy. There was no apparent deterioration of wear reduction properties even though there was very little lime left on the railhead after the first run. A second coat of slaked lime was sprayed on the rail prior to the third and final run when the test sample was loaded at a nominal bearing pressure of 300 psi.

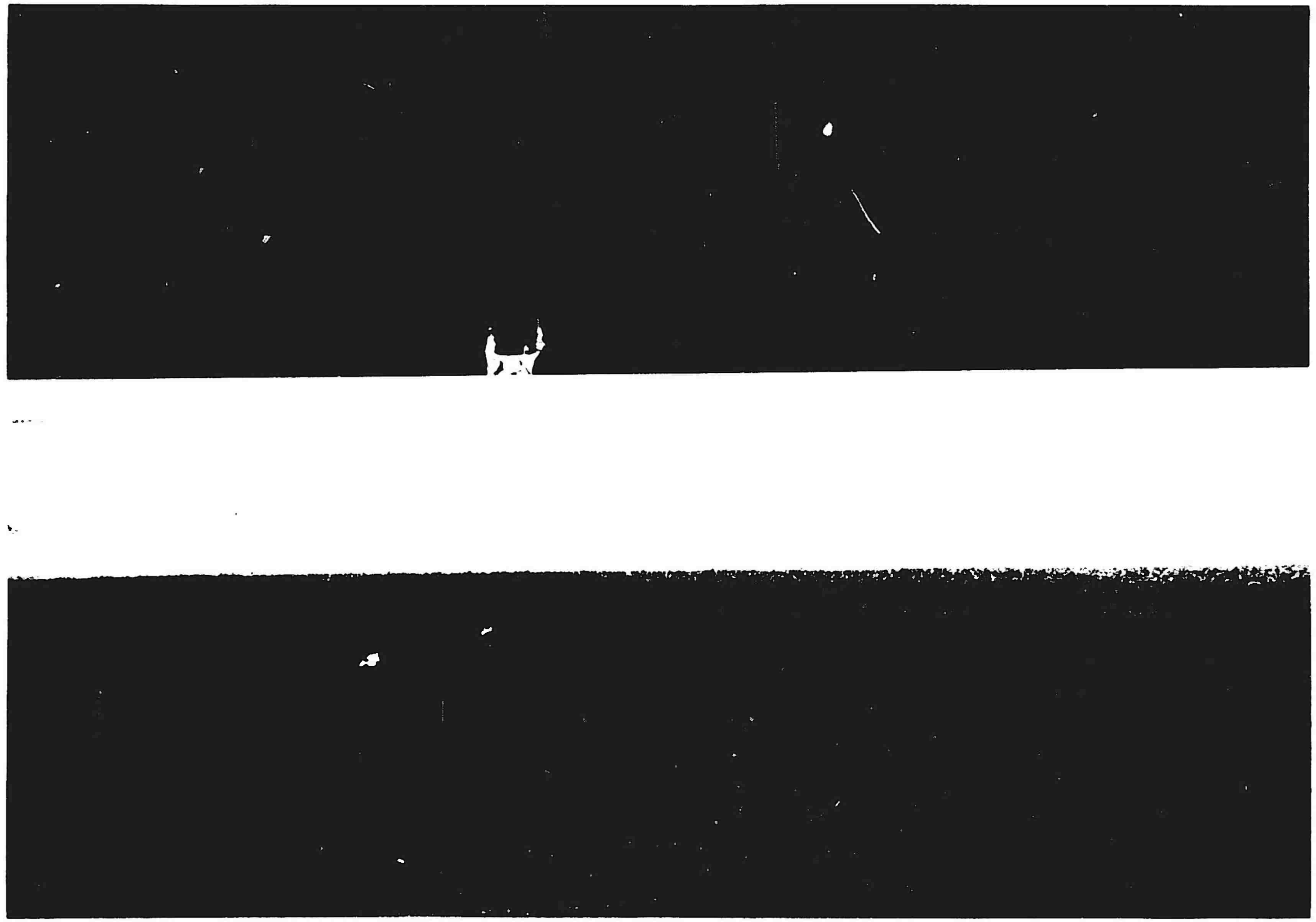


FIGURE 26. Top of Railhead with Metallized Aluminum Coating
Smooth Section

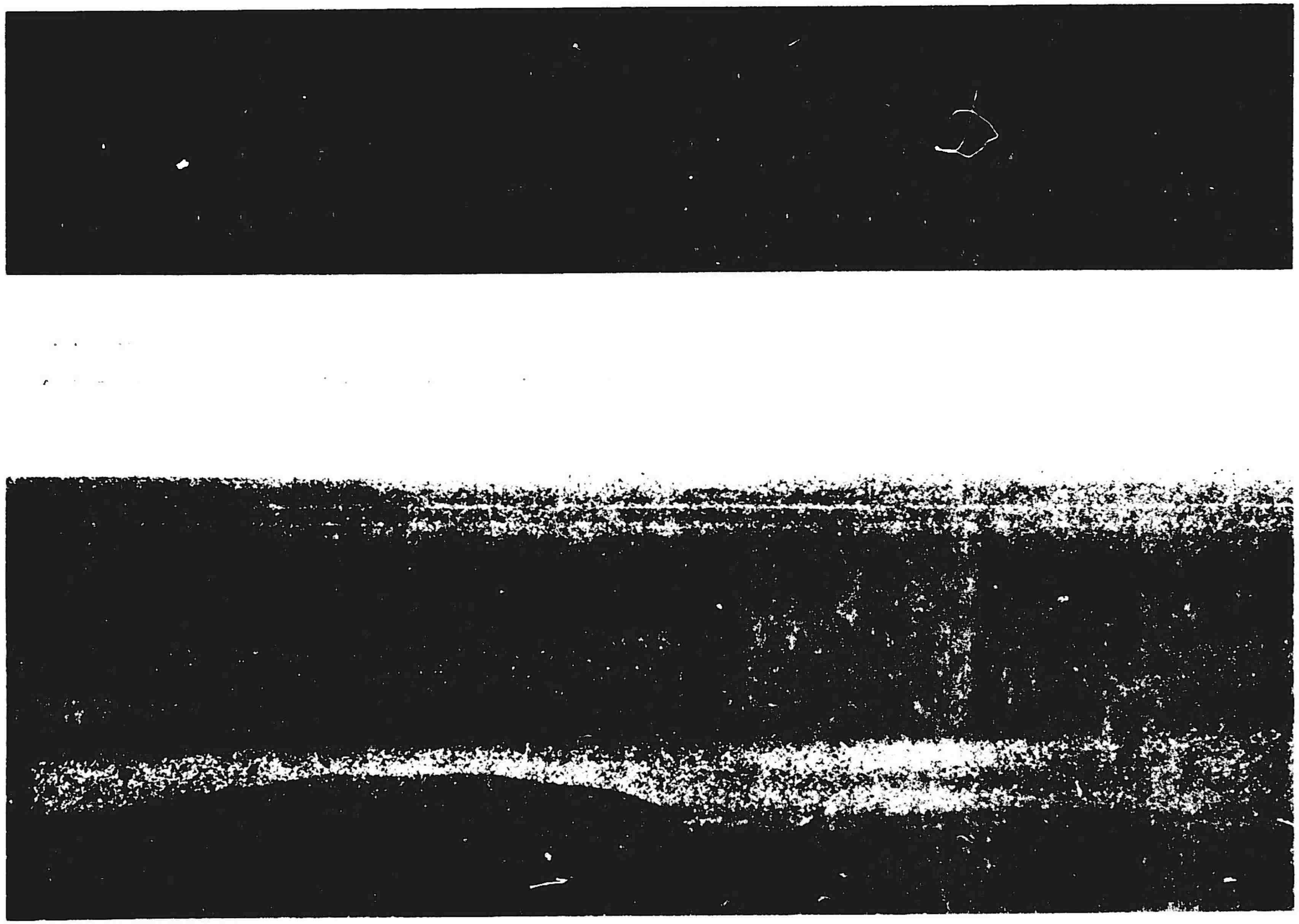


FIGURE 17. Top of Railhead with Metallized Aluminum Coating
Gouged Surface

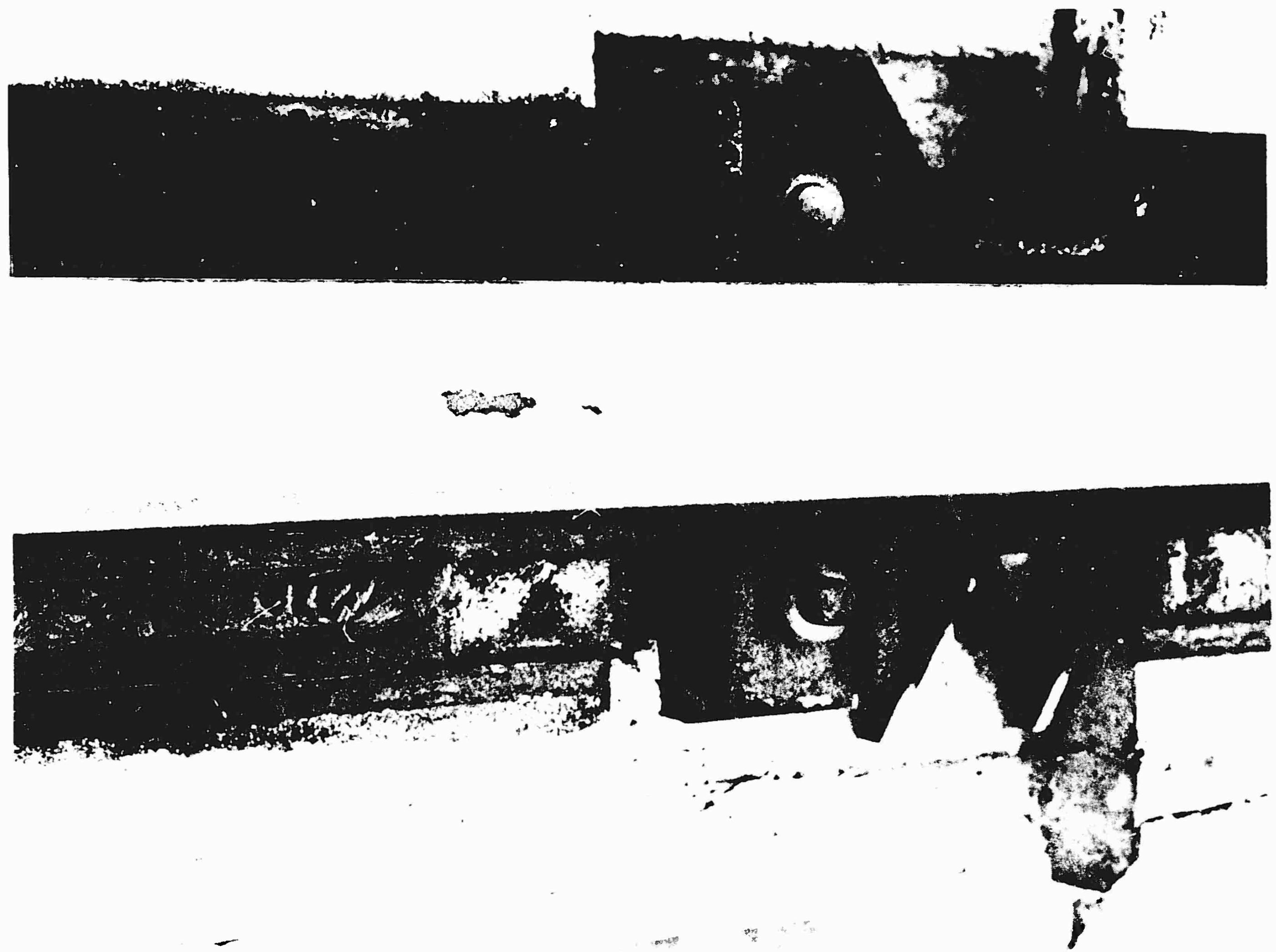


FIGURE 28. Top of Railhead with Metallized Aluminum Coating Flaking Surface Due to Poor Adherence

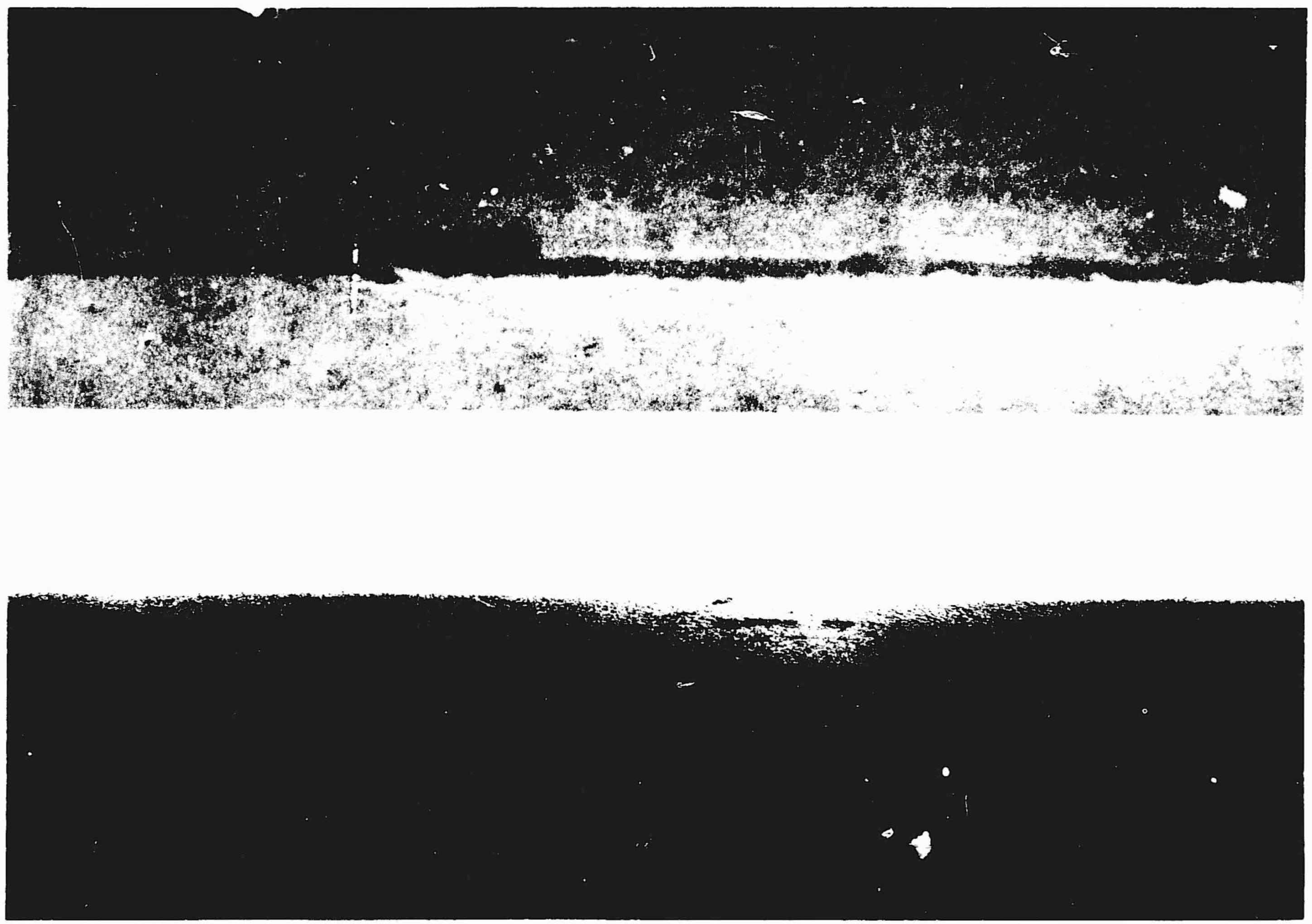


FIGURE 29. Top of Railhead with Metallized Aluminum Coating
Post-run Condition

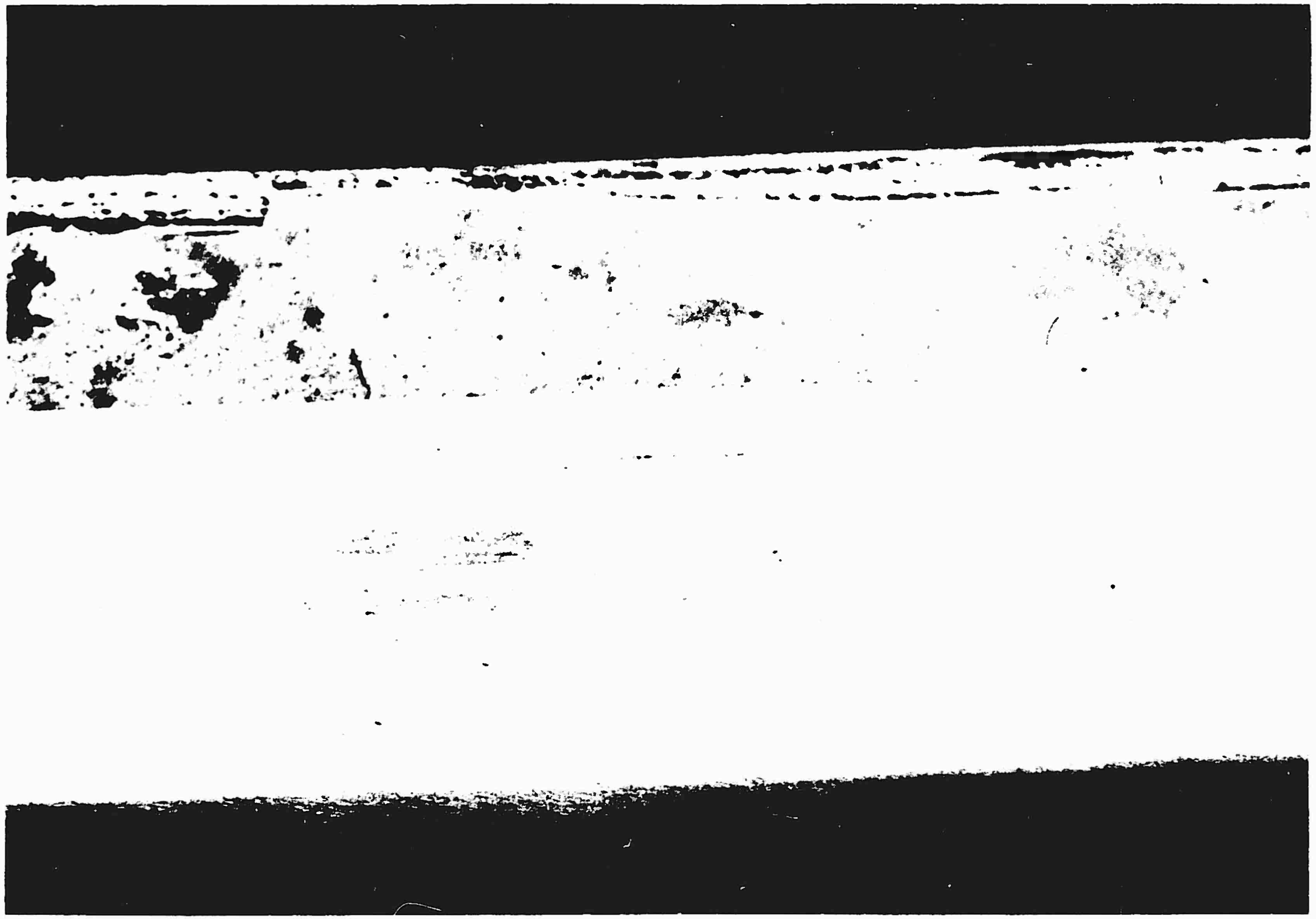


FIGURE 30. Top of Railhead with Metallized Aluminum Coating
Path of Test Sample Along Center of Railhead

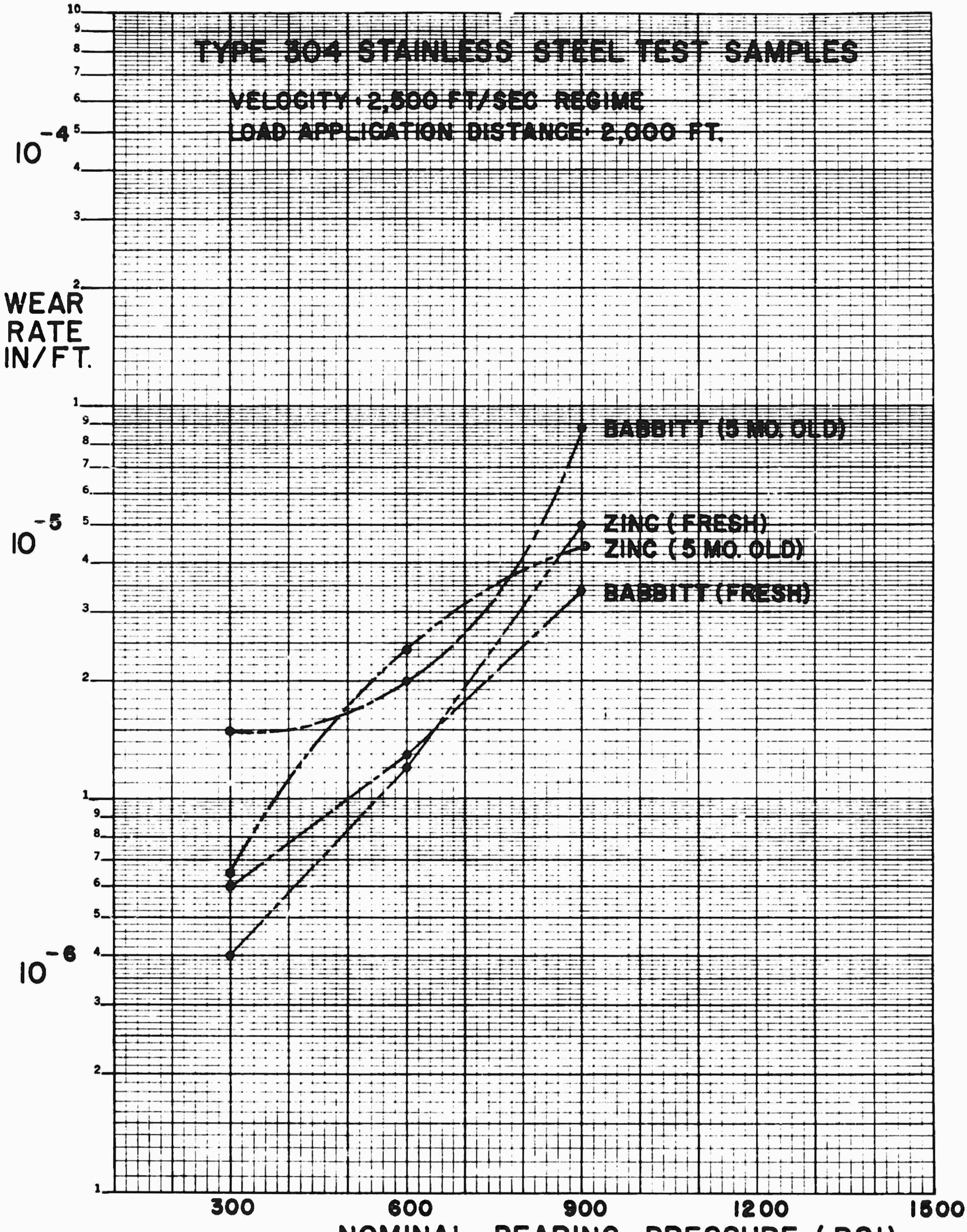

TYPE 304 STAINLESS STEEL TEST SAMPLES
VELOCITY 2,500 FT/SEC REGIME
LOAD APPLICATION DISTANCE 2,000 FT.
WEAR RATE IN/FT.
10^{-4}
10^{-5}
10^{-6}
BABBITT (5 MO. OLD)
ZINC (FRESH)
ZINC (5 MO. OLD)
BABBITT (FRESH)
300
600
900
1200
1500
NOMINAL BEARING PRESSURE (PSI)

FIGURE 31

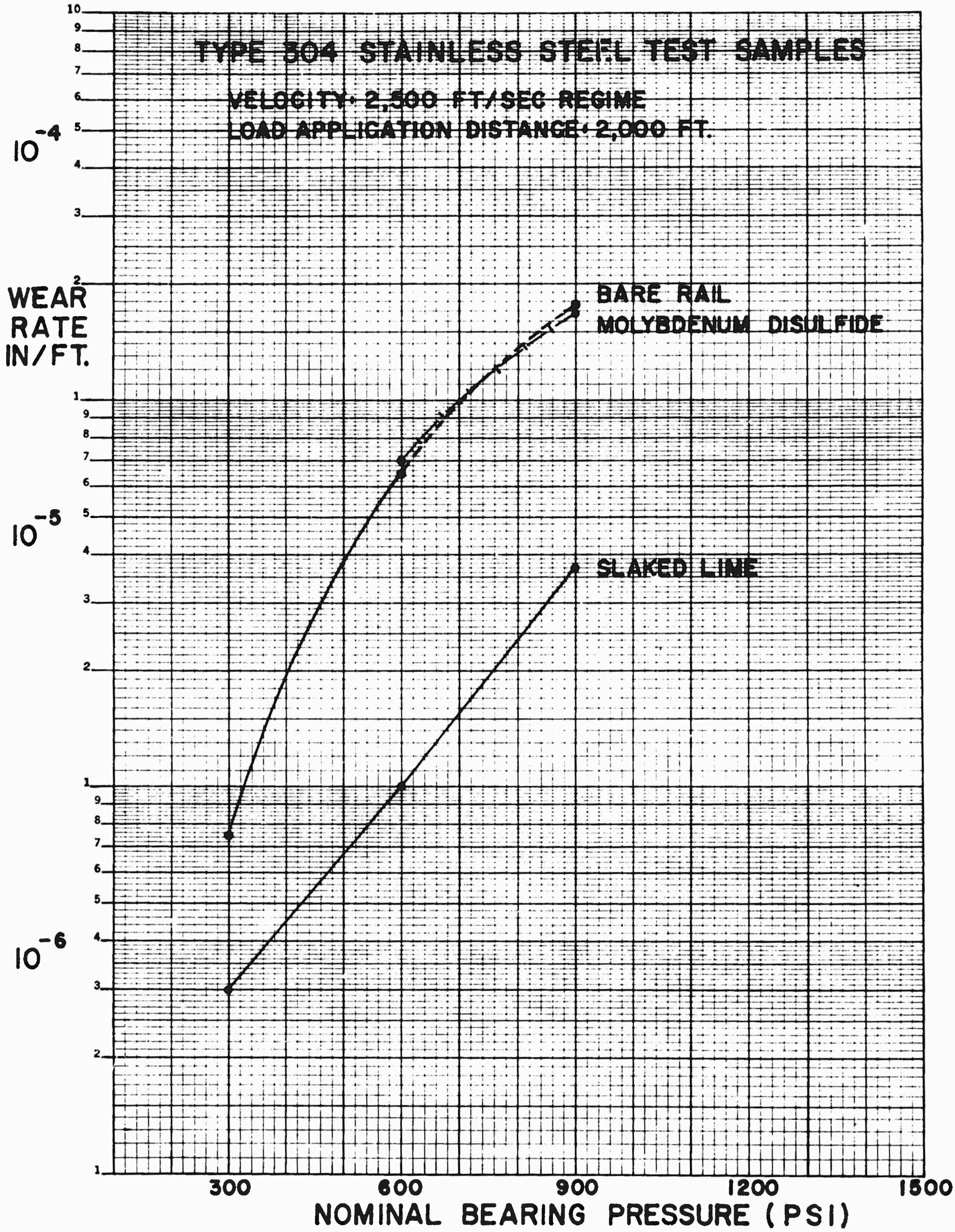

TYPE 304 STAINLESS STEEL TEST SAMPLES
VELOCITY: 2,500 FT/SEC REGIME
LOAD APPLICATION DISTANCE: 2,000 FT.
WEAR RATE IN/FT.
10^{-4}
10^{-5}
10^{-6}
BARE RAIL
MOLYBDENUM DISULFIDE
SLAKED LIME
300
600
900
1200
1500
NOMINAL BEARING PRESSURE (PSI)

FIGURE 32

It is felt the slaked lime reduced sample wear partly because of the following reaction:

$$CaO + H_2O \rightleftarrows Ca(OH)_2$$

Considerable thermal energy is used in calcining the lime and in converting the released water to steam. It is also known that fused lime (CaO) has a platelet structure with low shear strength.

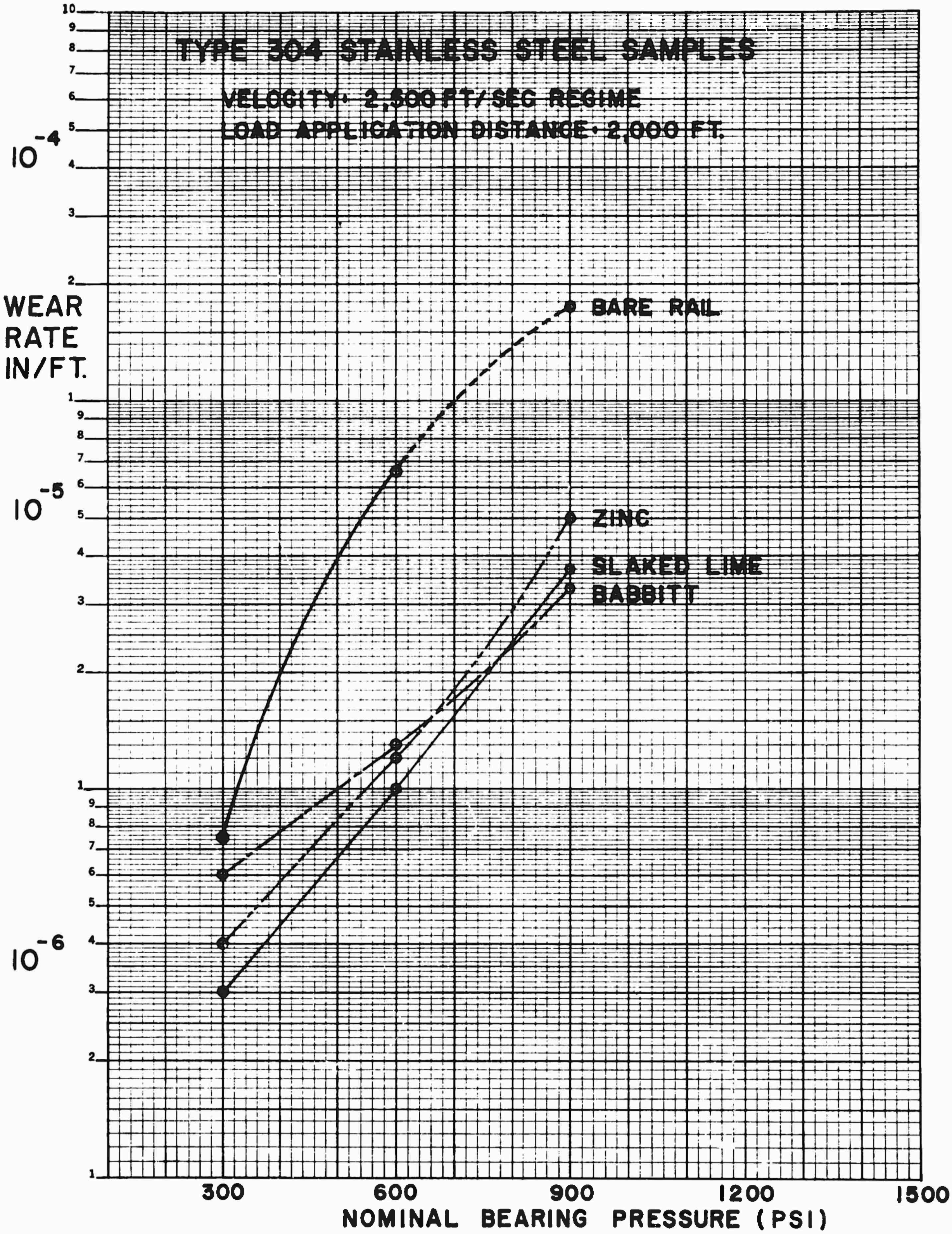
Unfortunately, the slaked lime test series was fired under non-standard conditions. It rained and hailed intermittently during the day, and previous work has ascertained that wear is reduced when the track is wet or covered with a fresh, powdery layer of rust. Since the slaked lime wear data were obtained under non-standard conditions, they must be interpreted with caution.

The wear data obtained on the bare rail, fresh coatings of zinc, babbitt, and slaked lime, are compared in Figure 33. The zinc, babbitt, and slaked lime curves are quite similar, and all indicate considerable reduction in wear rate in comparison to the bare rail curve.

At this time slaked lime would be the undisputed coating of choice if the data had been collected under standard conditions, because it is both economical and operationally practical, and it would not interfere with a current rail honing program.

In view of the wear theory, current bearing material investigations have largely been limited to refractory metals and their alloys. Unfortunately molybdenum has not been the cure-all because of the inconsistency of its mechanical properties and because of its brittleness at ambient temperature. A very modest program has been instituted under the current SRI contract to improve the mechanical properties and ambient temperature ductility of molybdenum base alloys.

The laboratory work is underway at SRI, and it is believed the problem area has been narrowed down to brittle microconstituents concentrated in the grain boundaries and depression of the ductile to brittle fracture transformation temperature. These microconstituents are controversial, but appear to be oxides of molybdenum. The laboratory effort is directed toward either reducing these oxides or diffusing them away from the grain boundaries into the grains proper. Alloy compositions are being sought that will lower the ductile to brittle fracture transformation temperature and raise the recrystallization temperature.



TYPE 304 STAINLESS STEEL SAMPLES
VELOCITY: 2,500 FT/SEC REGIME
LOAD APPLICATION DISTANCE: 2,000 FT.
BARE RAIL
ZINC
SLAKED LIME
BABBITT
WEAR RATE IN/FT.
10^{-4}
10^{-5}
10^{-6}
300
600
900
1200
1500
NOMINAL BEARING PRESSURE (PSI)

FIGURE 33

The wear resistance of Type 304 stainless steel, SAE 4140 steel, and commercially pure vanadium, are compared in Figure 34. The single data point on 4140 indicates wear resistance similar to stainless steel; and the two data points on vanadium indicate better wear resistance than stainless steel.

The wear test of tantalum was unsuccessful as noted in Run Number 56 in the table on page 30. The sample consisted of a tantalum bearing face plate welded to molybdenum backing. It is suspected that the weld joint at the tantalum-molybdenum interface failed and the tantalum plate was lost during the run.

Besides track coatings and bearing materials, dynamic loading was also considered. The test samples were pneumatically loaded, for two reasons: (1) to provide ease of testing at a variety of pressures, and (2) to attempt to simulate operational conditions. The slipper-rail impacts play an important role in sled vibrational environment as well as slipper wear.

The schematic diagram from Reference 2 (Fig. 35) illustrates the pneumatic loading and friction measurement systems in the SRI test slipper. The springs are normally heat-treated beryllium copper plates. These were replaced by thicker and stiffer steel plates for Run Number 49 as shown in the table on page 30. The test sample exhibited an average wear rate of 4.8×10^{-5} inches per foot of travel.

It is accepted that the test sample assembly oscillates in a vertical direction during a test. One of the reasons for this motion is irregularities in the railhead surface. The increased wear with the heavy assembly might be explained on the basis of the greater inertial loading associated with the increased system mass.

On the other hand, since all systems, regardless of mass and loading, are known to leave the rail frequently, it might be argued that the heavier system would remain off the track longer than the light system (assuming the same restoring force) and therefore might spend less time on the track and would encounter a fewer number of impact loads. It is conceivable that a particular set of conditions (depending probably on high strength of the slider material) constitute a crossover point at which frequency of impacts and time on track become more important than the magnitude of impact loads. Such a reversal of wear behavior was observed experimentally at the SNORT, where wear increased with unsprung mass with one set of conditions and decreased with another.

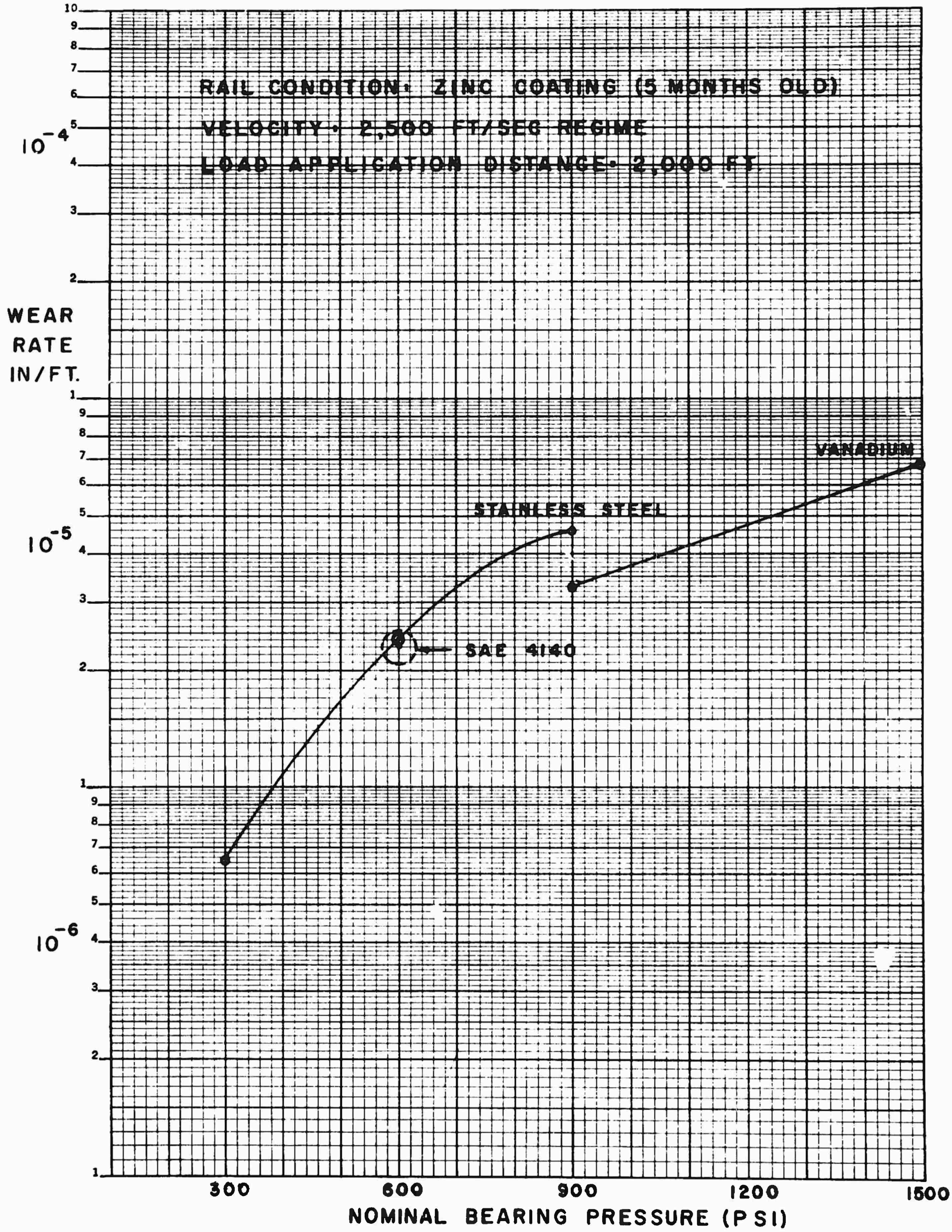

RAIL CONDITION: ZINC COATING (5 MONTHS OLD)
VELOCITY: 2,500 FT/SEC REGIME
LOAD APPLICATION DISTANCE: 2,000 FT.
WEAR RATE IN/FT.
10^{-4}
10^{-5}
10^{-6}
VANADIUM
STAINLESS STEEL
SAE 4140
300
600
900
1200
1500
NOMINAL BEARING PRESSURE (PSI)

FIGURE 34

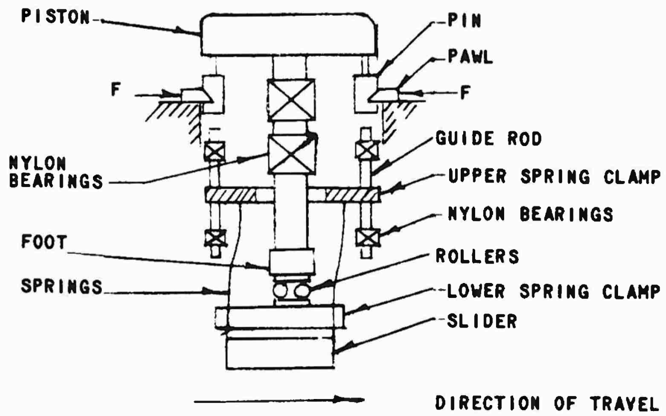


FIGURE 35. Pneumatic Loading and Friction Measurement Systems Schematic Diagram

REFERENCES

1. Wolfson, M. R., "Shoe Design and Material Studies for High-Speed Sliding-Friction Applications at SNORT," NAVORD Report 5626, NOTS 1845, U. S. Naval Ordnance Test Station, China Lake, California, 27 August 1958.

2. Sauer, Fred M., "Fundamental Mechanism of Wear and Friction of Unlubricated Metallic Surfaces at High Sliding Speeds," NAVORD Report 5452, NOTS 1729, U. S. Naval Ordnance Test Station, China Lake, California, 15 April 1957.